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An Investigation Into the Effects of Sprue Attachment Design on Porosity and Castability

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DEDICATION

This Thesis, and the effort it represents, is dedicated to the following five people who have supported me throughout my life:

To my deceased father, John J. Levon, who instilled in me the desire for knowledge and taught me that "any job worth doing, is one worth doing well."

To my mother, Corinne Levon Carr, who provided me with unending emotional and financial support for so many years and taught me the importance of caring about others.

To my stepfather, Jack L. Carr, who filled-in as best he could following the death of my father.

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AN INVESTIGATION INTO THE EFFECTS OF

SPRUE ATTACHMENT DESIGN ON

POROSITY AND CASTABILITY

John Alan Levon, M.S.

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at San Antonio

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Many variables are involved in the process of fabricating a dense dental casting which accurately duplicates the wax pattern. The type of sprue design that is utilized has been shown to play a important role in the casting process. The literature is filled with conflicting results and conclusions regarding proper sprue attachment design.

The objective of this investigation was to evaluate the effects of four different sprue attachment designs (Gradual Constriction, Abrupt Constriction, Flared, and Straight) on the porosity and castability of three

different dental casting alloys: Firmilay, a Type III gold alloy; Jel-5, a palladium-silver alloy; and Rexillium III, a base-metal alloy.

In order to investigate this problem, working refractory dies were fabricated via the indirect impression technique from a master machined die. A special sculpturing device was utilized to standardize wax patterns with knife-edge margins on the refractory dies. The knife-edge margins were shown to discriminate differences in castability.

A metal master sprue for each design studied was machined from an aluminum alloy and duplicated via a wax injection process. The duplicated wax sprues were attached to the standardized wax patterns utilizing a parallelometer. The sprue/wax pattern/refractory die combinations were invested following accepted dental laboratory procedures. All castings were made in the same broken arm centrifugal casting machine while following the specific manufacturer's guidelines for melting and casting each of the three dental casting alloys.

The completed castings were benched cooled and manually divested. These castings were then grossly cleaned by hand, before being placed in distilled water in an ultrasonic machine for further cleaning. The sprue buttons were removed at the midpoint of the sprues and the castings were then embedded in a clear polyester resin prior to their sectioning in half with a diamond saw. A distinctly defined casting/resin interface was obtained on the plane of section via metallographic polishing procedures.

Porosity was evaluated by four board certified prosthodontists, who rank ordered unidentified photographs of each alloy investigated in a continuum from least area of porosity to greatest area of porosity. After polishing, the area of the sprue-crown junction was photographed at a magnification of approximately X50 in a metallographic light microscope. A Spearman Rank Correlation Coefficient test demonstrated significant interrater reliability ($p<.001$).

A Kruskal-Wallis one way analysis of variance revealed a significant difference between the four sprue attachment groups for Firmilay ($p<.01$). A Mann Whitney Pairwise analysis of the test groups for Firmilay demonstrated that the Straight and Flared sprue attachment groups were less porous than the Gradual and Abrupt Constriction groups ($p<.01$ for Straight; $p<.05$ for Flared).

For Jel-5, a Kruskal-Wallis one way analysis of variance demonstrated a significant difference between the four sprue attachment groups ($p<.057$). A Mann Whitney Pairwise analysis of the test groups for Jel-5 revealed that the Straight and Flared sprue attachment groups were less porous than the Gradual Constricted group ($p<.05$ for Straight; $p<.052$) for Flared).

For Rexillium III, a Kruskal-Wallis one way analysis of variance showed that no significant difference existed between the four sprue attachment groups ($p=.17$). However, a Mann Whitney Pairwise analysis of the test groups for Rexillium III revealed that the Straight and Flared sprue attachment groups were less porous than the Gradual Constricted test group ($p<.05$).

Castability was measured by determining the width of the cast meniscus of the margins by utilizing the Gaertner Measuring Microscope. The measurements, in microns, of the cast margins were recorded for both the margin proximal and distal to the sprue attachment area.

For Firmilay, a two way ANOVA revealed that sprue attachment design was significant across the groups ($p<.0001$). The interaction between the margin location and sprue attachment design was found to also be significant ($p<.0001$). A Scheffe F-test analysis of means showed that the Straight and Flared sprue attachment groups had significantly smaller cast proximal margins than the Gradual Constricted or Abrupt Constricted sprue attachment groups ($p<.05$). In addition, the Gradual Constricted sprue attachment group had significantly smaller cast proximal margins than the Abrupt Constricted group ($p<.05$). There was no significant difference between the Straight and the Flared sprue attachment groups. The Straight sprue attachment design produced the smallest mean cast marginal width (140.022 microns), followed closely by the Flared design group (144.744 microns).

For Jel-5, a two way ANOVA revealed that sprue attachment design was significant across the groups ($p<.0047$). No interaction was found between the margin location and sprue attachment design ($p=.9867$). A Scheffe F-test analysis of means revealed that no sprue attachment group exhibited a significant superiority in regards to producing a smaller cast margin. The Flared sprue attachment design resulted in the smallest mean

cast marginal width (101.456 microns); however, this mean width was not significantly smaller than the other three designs.

For Rexillium III, a two way ANOVA revealed that sprue attachment design was significant across the groups ($p<.0093$). The interaction between the margin location and sprue attachment design was found to also be significant ($p<.0234$). A Scheffe F-test analysis of means showed that the Flared sprue attachment group had significantly smaller cast proximal margins than either the Abrupt Constricted or Straight sprue attachment groups. The Flared sprue attachment design resulted in the smallest mean cast marginal width (89.467 microns); however, this was not significantly smaller than the other designs.

Based on the results of this investigation a Flared or a Straight sprue attachment should be utilized to minimize porosity in castings made with Firmilay, Jel-5, and Rexillium III. A Flared or a Straight sprue attachment should be used to optimize castability when using Firmilay. A Flared sprue attachment should be utilized to optimize castability with Rexillium III; and no definitive conclusion can be made concerning the castability of Jel-5.

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I. INTRODUCTION

The "lost wax" process to cast gold and other metals has been utilized by the arts for thousands of years but the dental application of this casting technique did not become a reality until the turn of the twentieth century. The introduction of the dental casting of gold by Taggart in 1907, revolutionized dental care. During the past 82 years, the many variables involved in the lost wax casting process have been extensively studied and evaluated. Most of the technical considerations involved in the dental casting of gold and other alloys have been effectively worked out. However, a controversy exits in the dental literature today in regards to the appropriate sprue attachment design which is to be utilized in crown and fixed partial denture castings.

Conflicting results and conclusions regarding sprue design have been reported by numerous researchers. Crawford (1940) was one of the first to recognize the importance of sprue size and shape and recommended the use of a straight "short thick" sprue. Asgar and Peyton (1959) stated that "...flaring of the sprue may facilitate the flow of molten gold into the cavity." They demonstrated that a flared sprue attachment eliminated the porosity on the inner surface of gold castings. This opinion was not shared by Strickland and Sturdevant (1959), who studied the effects of twenty-three casting variables on porosity. They stated that "...adding a bulk of wax at the site of the sprue attachment did not alter the occurrence of porosity."

Nielsen and Ollerman (1976) agreed with Asgar and Peyton (1959) by recommending a flared sprue attachment that would "...spread the molten metal heat over an increased area..." and thereby prevent "suckback" porosity. Craig (1985) recommended flaring the sprue at the point of attachment in order to minimize turbulence in the molten alloy, to allow for an even flow of metal into the mold, and to decrease porosity at the sprue-wax pattern junction.

McLean (1980) stated that porosity in the area of sprue attachment could be prevented by placing a constriction at the sprue-wax pattern junction. Englemann and Blechner (1981) also recommended the use of a

constricted sprue. They postulated that by using a constricted sprue a "nozzle effect" would be created which would increase the speed of the molten alloy as it entered the mold and thus result in a denser casting. Rousseau (1984) recommended a sprue design similar to Mclean's. Rousseau stated that the "tapered" sprue prevented porosity at the sprue junction. Grunberg and Lutz (1985) stated that constricted sprues created a Venturi effect and they recommended their use to obtain quality castings.

Wagner (1980) advocated the use of a straight sprue. Sperner and Bramer (1982b) felt that straight sprues should be attached to the wax pattern without any flaring or constricting. Compagni, Faucher, and Yuodelis (1984) stated that sprue design was more critical than the type of casting machine or heat source. They found the greatest amount of casting porosity with McLean's bottleneck-constriction and concluded that constrictions should not be utilized with straight sprues.

Verrett and Duke (1989) in a well-controlled study demonstrated that with a gold-palladium alloy containing 51.5% gold and 38.5% palladium (Olympia, J.F. Jelenko & Co., Armonk, NY) both the straight sprue and the flared sprue resulted in significantly less porosity than the abrupt or gradual constricted sprue in the area of sprue-casting junction. He also demonstrated that better castability could be obtained with Olympia alloy when either a straight or a flared sprue was utilized.

The design of the sprue attachment is a very important factor in the casting of dental restorations. The sprue is the part of the wax pattern that provides a channel through which the molten alloy enters the investment to ultimately fill the mold space. Castability can be defined as the relative ability of a molten metal to replicate a wax pattern. Manufacturers and researchers have recommended the following methods for sprue attachment:

1. A constricted attachment where there is an abrupt decrease in the diameter of the sprue at the site of attachment.

2. A bottleneck attachment that has a more gradual constriction of the sprue diameter at the site of attachment.

3. A flared attachment that gently blends sprue into wax pattern.

4. A straight attachment where there is no change in the diameter of the sprue.

From the preceding discussion it is quite obvious why there presently exists so much confusion in the dental laboratory. The purpose of my investigation is to identify the sprue attachment design which results in optimal castability and the least amount of porosity for each of three commonly used dental alloys: a Type III gold alloy, a palladium-silver alloy, and a base-metal alloy. The porosity and castability obtained with each sprue attachment design for each of the three alloys will be evaluated.

Research Hypothesis

A sprue attachment design significantly affects the porosity in dental castings and/or the completeness of these castings. $P < 0.05$.

Null Hypothesis

There are no statistically significant differences in the porosity obtained in castings and/or in the casting completeness with the described sprue attachment designs. $P > 0.05$.

II. LITERATURE REVIEW

A. Early History of Dental Gold Casting

For thousands of years mankind has been casting gold and other metals via the "cire perdue" or "wasting wax" process. Hollenback (1962) reported on the utilization of the lost wax technique by the Chinese 5,000 to 6,000 years ago and later by the Etruscans, Mayans, and the Phoenicians. The casting of bronze statues in Babylon around 2300 B.C. is perhaps the earliest written account describing the use of the "wasting wax" technique (Stryker 1911). A series of eleventh century books entitled "An Essay Upon the Various Arts," described in detail the use of the lost wax casting process and its application in the arts. Their author, Theophilus, meticulously described the casting of handles for a silver cup in such detail that the process could have been replicated (Craig 1985). The utilization of the lost wax casting process was explained in a book written in 1558 by Benvenuto Cellini entitled Trattato Della Scultura. Cellini devoted special attention to the sprue system and established many of the principles of the lost wax casting art (Prinz 1945 and Weinberger 1948).

Before the introduction of the lost wax process, the technique of swaging gold to a desired shape was the most common method of working gold for dental use (Prinz 1945). Complete metal crowns, known as "gold shell" crowns, were introduced by Morrison in 1869 (Malone 1978). These gold shell crowns were made from five dollar gold coins which were rolled to a 28-29 gauge thickness. A band was prepared, festooned, and soldered to form the axial surfaces. The cusps were formed by swaging gold into metal die plates and this occlusal surface was then soldered to the axial band. In 1878, Richmond introduced his "gold collar crown" which consisted of a gold shell crown soldered to a gold post that extended into the root canal (Hagman 1980a).

The investing of a wax pattern in a two-piece plaster mold with a carved sprue canal was first described by Martin (1892) and Reese (1894). A narrow band of iron or tin was used to tie the mold halves together and superheated gold was poured into the mold cavity, after wax elimination.

Similar techniques for the fabrication of "laboratory fillings" or "cast fillings" were described by Swasney (1890), Foster (1894), and Alexander (1896). Platinum foil was burnished into an inlay cavity to form a matrix which was embedded in plaster. Gold solder was then flowed into the matrix. Philbrook (1896) reported on the first inlay fabricated without the use of a platinum or gold foil matrix.

In a lecture to the New York Odontological Society, William H. Taggart presented in minute detail his lost wax process and demonstrated the Taggart casting machine, that utilized nitrous oxide for casting pressure (Taggart 1907). His scientific proposal revolutionized dentistry and marked the birth of modern crown and bridge prosthodontics.

In addition to the nitrous oxide casting pressure of Taggart, other sources of casting pressure have been recommended. A steam pressure casting method was described by Solbrig in 1906 (Henning 1972, Hagman 1976, and Hoffman-Axthelm 1981). The casting ring was held in modified pliers and the gold was melted in the crucible. The top jaw of the pliers, lined with wet asbestos, was closed against the molten alloy which forced the gold into the mold by steam pressure (Platshick 1908). A casting machine similar to Taggart's was developed by Burns. Casting pressure was supplied by air pressure produced by a bicycle pump (Hagman 1980b).

The first spring loaded horizontal centrifugal casting machine was introduced by Jameson in 1907 (Prinz 1945). Utilization of a cowbell as an investment flask was suggested by Campbell (1911). Molten metal was poured into the mold inside the cowbell, which was swung on a chain until the metal solidified. The "Den Pro" vertical hand cranked casting device and the "Ingersol" hand cranked horizontal casting machine were being used by 1918 (Hagman 1980b).

Frink (1908) introduced vacuum casting pressure. In this technique, a syringe was attached to the base of a ring in which gold was melted and the syringe plunger was pulled down to provide casting pressure. Ransom and Randolph patented the "Elgin Pig" casting machine in the early 1920's (Hagman 1976). This casting machine consisted of an iron tank and an exhaust pump which created a vacuum.

Centrifugal pressure and pressure differential have been the only two forces used in all of the dental casting machines invented since the

early 1900's (Leinfelder 1982). However, casting methods can be further subdivided into the following categories:

1. Centrifugal casting.
2. Air or gas pressure casting.
3. Static pour or gravity casting, rarely used due to incomplete metal flow into thin areas.
4. Vacuum pressure casting.
5. Combination of methods, including air pressure/vacuum and centrifugal/vacuum (Sperner and Bramer 1982a).

B. Centrifugal Casting Factors

Both vertical and horizontal casting paths have been utilized in centrifugal casting machines. Due to design simplicity, the ability to cast both small and large patterns, and ease of operation, the centrifugal casting machines have enjoyed widespread popularity. Craig (1985) reported that there is little reason to favor one type of centrifugal machine over the other when handled properly.

The factors which affect the time required to cast gold by centrifugal force were reported by Myers (1941). He described the following equation for centrifugal casting force:

Casting = Proportionality Constant x Mass x Radius of Casting Arm x (Revolutions/second)^2 or $F = (K)\ (m)\ (r)\ (N)^2$. In addition, Myers found that the actual casting pressure in a centrifugal casting machine varied between 14.2 to 25 PSI. The variation was attributed to the increasing speed of the casting arm, the varying weight of the column of metal directly over the sprue, and the distance from the axis of rotation to the mass of the metal.

Henning (1972) reported that the casting pressure in a centrifugal casting machine could be increased by using a stronger spring or more winds, by increasing the mass of gold used, and by lengthening the casting arm.

C. Porosity

An inevitable occurrence in the casting process has been shown to be porosity. Leinfelder, Fairhurst, and Ryge (1963) demonstrated the presence of porosity when they consistently reduced the specific gravity of

a gold alloy via repeated castings. These authors also reported that a combination of casting variables were related to the amount of porosity. Their results reiterated earlier investigations by Ryge, Kozak, and Fairhurst (1957) and Sahs (1958).

Porosity can cause discoloration, weaken the casting, and cause leakage resulting in recurrent caries if it occurs on the surface of the casting (Phillips 1982). Phillips agreed with Leinfelder et al. (1963) when he stated: "Although the porosity in a casting cannot be prevented entirely, it can be definitely minimized by a proper technique".

Porosity was classified as internal or external by Ryge et al. (1957), who further defined subcategories of porosity within both groups. Their classification system has been used to describe and differentiate casting porosity as follows:

1. Internal Porosity

The two basic causes of internal porosity are: the interaction of gases with the alloy in a molten state and cooling and solidification properties.

a. Localized shrinkage porosity.

Among the first type of porosity recognized in the dental literature was localized shrinkage porosity. Coleman (1926), Asher and Comstock (1933), Sturdevant (1938), and Wilson (1941) have all described shrinkage porosity. Shrinkage porosity is usually found near or within the sprue attachment area and is the result of an incomplete feeding of molten metal during the solidification contraction from a liquid to a solid phase.

A short sprue of large diameter was attached by Sturdevant (1938) to the largest bulk of the wax pattern in order to reduce shrinkage porosity. A wax "reservoir" was placed by Wilson (1941) approximately 1/16 of an inch from the pattern in order to permit molten alloy from the reservoir to feed the solidifying casting.

b. Microporosity.

A type of casting defect caused by solidification shrinkage has been termed microporosity. If either the alloy casting temperature or the mold temperature is too low, the alloy will solidify rapidly upon entering the mold. A generalized porosity throughout the casting will result and is referred to as microporosity (Ryge et al. 1957).

c. Subsurface porosity.

Subsurface porosity is a cooling and solidification type of porosity and was first described by Ryge et al. (1957). Ady (1966) stated that subsurface porosity occurred when the molten alloy was fed too rapidly into the mold. This could occur with high mold or alloy casting temperatures and with short thick sprues. Molten alloy next to the investment formed a solidified skin while the central mass of gold remained molten and small porosities formed between the first and the last areas to solidify. Subsurface porosity is usually not apparent until the finishing and polishing procedures have altered the outer surface of the casting. Phillips (1982) stated that "the reasons for the presence of such voids have not been completely established."

d. Pinhole porosity.

The entrapment of gas during the solidification phase of the alloy results in pinhole porosity and has been characterized as round regular voids which are evenly distributed in the casting (Crawford 1940). As the temperature of the molten metal increases, the solubility of gases increases and as the metal cools, dissolved gases tend to be liberated. Some gas bubbles escape from the mold while others become entrapped. This type of porosity has been referred to as "blowholes" by Asher and Comstock (1933).

e. Gas inclusions.

Gas inclusion porosity usually involves voids which are larger, fewer in number, and more irregular than pinhole porosity. Ryge et al. (1957) reported that gases mechanically trapped or carried into the mold was the cause of gas inclusion porosity. Sahs (1958) stated that hydrogen and oxygen gases could become occluded in the molten alloy due to a poorly adjusted or positioned flame. He stressed the importance of using the reducing zone of the flame when melting alloys. Wagner (1979) postulated that improper wax elimination could result in porosity produced by gases. He believed that a "coal-like ash" remained when the wax was not totally eliminated. This residue would then be rapidly heated by the molten gold and gassing would occur.

2. External Porosity.

a. Back pressure porosity.

The first mention of "back-pressure" porosity in dental castings was by Myers (1932) and he referred to it as "molten metal rebound." Phillips

(1947), in describing a defect usually found on the internal wall of the casting below the occlusal surface, first utilized the term "back pressure porosity." This porosity occurred when the casting pressure was insufficient to force gases out of the mold cavity into the investment and out the open end of the ring. Phillips suggested using a longer sprue in order to place the pattern closer to the end of the ring.

The observation that the presence of entrapped air on the inner surface of the casting occurred more frequently with complete crowns was made by Brumfield (1950). He stated that hot gases on the "inside" of the crown flowed from five vectors at once (i.e. all vertical sides and occlusal side) and suggested the use of 10 gauge wax vent. The position of this wax vent should be 1/16" to 1/8" from the inner aspect of the occlusal surface in order to facilitate venting of hot gases. In addition, he demonstrated that the use of this vent was not a critical factor in obtaining sound castings.

Strickland and Sturdevant (1959) reported on ways to eliminate back pressure porosity. They found that 3 to 5 winds on a centrifugal casting machine or 20 PSI minimum pressure for air pressure casting machines produced a "high enough" casting pressure to eliminate back pressure porosity. In order to more easily vent gases, they recommended placing the pattern 1/4" from the end of the ring.

Phillips (1982) stated that "proper burnout, an adequate mold and casting temperature, and a sufficiently high water/powder ratio will help to eliminate this phenomena."

b. Suckback porosity.

Suckback porosity has been described as a form of localized shrinkage porosity and occurs on the external surface of a casting near the sprue, usually on the inner aspect of a complete crown (Nielsen and Ollerman 1976). The author believed that a "hot spot could be created on the interior mold wall caused by inrushing molten high-fusing alloy, ...probably raising the temperature of this region by 300 to 400^{o}F. The last portion of the casting to solidify was this superheated area. Flaring the sprue attachment to the wax pattern and reducing the casting temperature of the alloy were two ways, described by Nielsen and Ollerman, to eliminate suckback porosity.

c. Incomplete casting.

Crawford (1940) and Brumfield (1950) reported that foreign particles such as small fragments of investment may be carried into the mold resulting in surface voids. External porosity can also be caused by incomplete wax elimination. Hot gases cannot be vented due to a blockage of the investment pores and results in a back pressure which could inhibit the molten allo from completely filling the mold space.

3. Optimal Casting Conditions for Minimal Porosity.

Ryge et al. (1957) suggested that the inevitable porosity obtained in dental castings could be eliminated through the proper manipulation of the sprue, the alloy casting temperature, and the mold temperature. In an evaluation of five variables on porosity, Kelly (1970) found that the most significant variable was mold temperature, followed by venting, investment type, and sprue size. The alloy casting temperature had no significant effect. Custer and Diemer (1967) studied the occurrence of porosity produced by nine different casting machines by comparing the specific gravity of gold in the wrought state and the cast state. By calculated the reduction in specific gravity, they concluded that porosity was not a significant clinical problem if mold temperature, casting temperature, and casting pressure were in an acceptable range.

Ingersoll and Wandling (1986) and Naylor (1986) described in detail the "Laws of Casting" as they pertain to spruing, investing and burnout, and casting. The seventeen laws are as follows:

a. Attach the sprue to the thickest cross-sectional area of the wax pattern.

b. Orient the margins of the wax pattern to the right and mark their location. This assures that the centrifugal, rotational, and gravitational forces on the molten alloy are used to their proper advantage.

c. Place the wax pattern in a cold zone of the investment mold, and position the reservoir in the heat center of the ring. This improves the likelihood that casting porosity will occur in the reservoir rather than in the restoration.

d. The reservoir must have enough molten metal available to fill the shrinkage that occurs within the restoration.

e. Do not cast a button if a runner bar, or other internal reservoir, is used.

f. Turbulence must be minimized, if not totally eliminated. Use smooth gradual pathways. Avoid sharp turns, restrictions, and impingement on flat surfaces.

g. Select a casting ring of sufficient diameter and length to accommodate the pattern or patterns to be invested. The patterns should be spaced 1/4" apart with at least 3/8" of investment between the patterns and the ring liner.

h. The surface tension of the wax pattern must be reduced. This enables the casting investment to wet the patterns more completely.

i. Weigh all casting investment powder and measure all investment liquids to assure a precise and consistent liquid-powder ratio.

j. Eliminate the incorporation of air in the casting investment during mixing and pouring. Vacuum mixing is highly recommended.

k. Allow the casting investment to set completely before beginning the burnout procedure.

l. Use a burnout technique that is specific for the type of patterns used (wax versus plastic) and suitable for the particular casting alloy selected.

m. Adequate heat must be available to properly melt and cast the alloy selected for use.

n. Use the REDUCING ZONE of the casting torch to melt the alloy and NOT the oxidizing zone when torch casting.

o. Enough force must be provided to cause the liquid alloy to flow into the heated mold, regardless of the type of casting machine used.

p. Cast to your margins. In a centrifugal casting machine the margins should be oriented downward and to the right.

q. Allow the ring to bench cool before quenching.

D. Castability

The definition of the term "castability" is the ability of an alloy to completely fill a mold space. Poor or incomplete castability can result in short incompletely cast margins. The following variables may affect the castability of a dental alloy: sprue design, mold temperature, fusing and casting temperature of the alloy, type of casting machine, casting force, burnout time, mass of the alloy being cast, and the geometry of the mold space (Verrett and Duke 1989).

To evaluate the casting ability of dental alloys, many direct and indirect investigations have been performed utilizing various methodologies. The current experimental designs include:

1. Castability As A Function Of The Fit Of Dental Restorations.

Christiansen (1966) utilized visualization and explorer palpation of the margins of cast restorations on stone dies. Teteruck and Mumford (1966) used microscopic examination of sectioned castings that were made on National Bureau of Standards M.O.D. dies.

The correlation between mold and casting temperature on the castability of two gold-palladium-silver based dental alloys was studied by Civijan et al. (1975). In order to obtain sharp margins on a complete crown casting, they had to increase the casting temperature from the manufacturer's recommended $2400^{o}F$ to $2650^{o}F$.

The fit and marginal integrity of complete and three-quarter veneer crowns that were cast from various alloys was investigated by Nitkin and Asgar (1976). They concluded that castings made from non-noble alloys were more complete when the alloys were superheated and that the fit of the non-noble alloys was inferior to type III and low gold alloys. Duncan (1982) evaluated the casting accuracy of four nickel-chromium alloys along with a precious metal alloy (Jelenko "O"). He utilized marginal fit of the cast copings as his parameter for determining casting accuracy.

Younis (1977) measured the ability to cast a spiral shaped wax pattern in investigating the marginal completeness and fit of nine dental alloys. He concluded that a high gold content alloy (Jelenko "O") produced the best result followed by the low gold content alloys, and then the silver-palladium alloys.

The fit of fourteen high fusing ceramo-metal alloys was evaluated by Eden et al. (1979) utilizing a truncated metal cone die. They reported that non-noble alloys resulted in consistently undersized castings. Using a similar test pattern, Smith et al. (1980) measured the reproducibility of sharp margins.

Teteruck and Mumford (1966) expanded the parameters of study to include surface roughness and thermal expansion. Since incomplete seating on a test die was the only criterion used to determine the percent miscast, their methods have limited utility in the quantification of

castability. A means of differentiating surface roughness and thermal expansion from castability has not been demonstrated.

2. Castability As Determined By The Ability To Completely Fill Specially Designed Mold Forms.

a. Nylon line projections, filaments, and fibers.

A test pattern consisting of six diameters of nylon fishing line was developed by Vincent et al. (1977). Five millimeter long sections of fishing line ranging in diameter from 110 to 670 microns were aligned parallel to each other but perpendicular to a large wax cylinder. The ends of the six nylon lines were positioned 3 to 3.5 mm from the end of the casting ring by adjusting the sprue length. They discovered that the castability of five alloys varied according to the density of the alloy. By increasing the casting force, poor castability caused by low density was improved.

Dewald (1979) demonstrated that to insure maximum casting completeness in centrifugal casting, the pattern should be angled downward from the sprue in the outer lower quarter of the trailing half of the casting ring, 90 to 135^{o} away from the sprue. His spherical pattern was 13 mm in diameter and contained 0.021 mm nylon bristles. These bristles extended outside the body of the pattern and were utilized to evaluate casting completeness.

A 14 gauge wax wheel with four 14 gauge spokes to which were attached six 20 mm long projections varying in diameter from 0.252 to 0.8 mm served as the standardized pattern in the study of Howard, Newman, and Nunez (1980). They compared the castability of 12 alloys to that of type III gold and contended that their pattern design could differentiate between the castability of the different alloys.

b. Spring-like coils.

Asgar (1973) recognized that fluidity and castability were crucial factors to be considered for casting alloys. Asgar first advocated the use of a spiral wax pattern to compare the castability of various alloys.

A test pattern in the shape of a "spring-like coil" was used by Preston and Berger (1977) to evaluate castability. Their pattern demanded that the casting be made counter to the centrifugal flow of the alloy. They felt that this pattern was impossible to cast completely, and therefore was a delineating indicator of castability.

An uncomplicated castability test pattern consisting of a nine inch long piece of ten gauge round sprue wax which was wound around two nails in a board one apart was utilized by Alleluia (1980b). Lacefield et al. (1983) used eight gauge half-round wax to fabricate spiral test patterns with seven complete turns 2 mm apart. They evaluated the number of turns of spiral which cast and the sharpness of the edge of the pattern. Gold alloys demonstrated greater castability than noble alloys.

c. Conical patterns.

Two sizes of 22 mm long conical patterns were utilized by Lewis (1977). The larger cone had a 7.0 mm diameter base which tapered to a 1.5 mm radius rounded apex, while the smaller pattern had a 5.0 mm diameter base which tapered to the same size apex. Gross shrinkage defects were not exhibited in the conical castings since unidirectional solidification could occur from the apex to the base, as long as the sprue size was sufficient.

d. Flat rectangular patterns.

A flat rectangular test pattern was suggested by Fusayama and Yamane (1973). Their pattern was 1 mm thick, 7 mm wide by 11 mm long, and was sprued by flaring a 2 mm diameter sprue pin. Different casting machines and casting pressures were utilized in evaluating the "soundness" of castings made from this standardized test pattern.

A standardized test pattern consisting of two rectangular plates was advocated by Preston and Berger (1977). A wax rectangular plate was joined to a rectangular polypropylene plastic plate to form a "V-shaped" pattern. This pattern was sprued at the midpoint of the junction between the two plates and cast. The interaction of the mold temperature, alloy casting temperature, and smoothness of the casting were evaluated. Visual and tactile assessment of the surface texture of the casting served as the basis for determining an optimal metal mold equilibrium for the alloys.

e. Saucer-shaped patterns.

The castability of three dental alloys using five different dental casting machines was evaluated by Asgar and Arfaei (1977, 1985). They used a saucer shaped pattern with three circles of different thicknesses. A castability ranking was obtained by comparing the diameter of the resultant casting to that of the wax pattern. The surface roughness,

porosity, and fit of the castings obtained from each alloy-casting machine combination was not evaluated.

A castability pattern similar to the one recommended by Asgar and Arfaei was suggested by Meyer et al. (1983). Their wax pattern consisted of a 24 mm diameter disk with a thin (0.05 mm) outer section perforated to produce four small "T-shaped" patterns. They calculated a castability index (C.I. in percent) from 25 different areas on the casting and concluded that their castability pattern was more sensitive to minor changes than the pattern of Asgar and Arfaei.

f. Nylon mesh grid patterns.

The castability of fifteen alloys cast according to manufacturer's instructions was evaluated by Whitlock et al. (1981). They utilized a pattern to test castability that consisted of a polyester mesh screen. This mesh screen had runner bars along two adjacent edges and was sprued at their junction. The "castability value" for each alloy tested was determined by counting the number of squares of the grid which were successfully cast.

A polypropylene mesh screen developed at the National Bureau of Standards was used by Kaminski et al. (1983) to compare castability of four test alloys with a Type III gold alloy. Mean castability values were found to vary from 100% to 97.6% in five generations of recast Type III gold alloy.

An extruded plastic screen mesh pattern containing 320 possible diamond shaped spaces was devised and utilized by Presswood (1983) to examine nine alloys. This test pattern exceeded the casting ability of all of the alloys tested under the conditions of this study. The best castability was exhibited by a silver-palladium alloy which exceeded a Type III gold alloy.

Mitchell and Kemper (1984) reported the mesh screen test of Whitlock et al. (1981) was unable to discriminate between alloys and casting conditions in which over 90% of the mesh was cast. They used a fine 50 gauge screen mesh and were able to demonstrate a difference in castability between non-noble alloys.

The castability of two Ag-Cu-Ge alloys and three noble metal alloys was investigated by Kois and Yuodelis (1984). They used a polyester mesh screen with a sprue modified to include a reservoir at the attachment to

the mesh pattern. They reported that the castability of the experimental alloys were superior to a Type III gold alloy and two silver-palladium alloys. However, since both experimental alloys were able to 100% cast the mesh pattern employed, the castability between the two alloys could not be differentiated.

Three modifications of a castability grid test which utilized commercially available single and double-grid wax patterns were advocated by Meyer et al. (1985). The authors reported greater differentiation of castability values among Co-Cr alloys with the double grid patterns. The castability of these alloys had not been differentiated by the dish test suggested by Asgar and Arfaei (1977) and later modified by Meyer et al. (1983).

Hinman et al. (1985) used Number 18 polyester sieve cloth for their mesh screen test pattern. They evaluated the castability of eighteen ceramo-metal alloys (13 base metal alloys and 5 noble alloys) and reported that their pattern was able to demonstrate differences in castability.

Covington et al. (1985) evaluated the castability of 32 different alloys (seven Ni-Cr, eight Ni-Be, eight Ag-Pd, two Pd, and six Cr-Co). They utilized three different mesh patterns in their investigation and reported that the Ni-Be group exhibited the best castability followed by the Ag-Pd group.

g. Blade or wedge-shaped patterns.

A knife edge pattern was introduced by Mackert, Moffa, and Jendressen (1975) to evaluate the castability of eight alloys. They used a Stanley "sheetrock" blade as a pattern. This blade was gold plated to eliminate corrosion, mounted on a crucible former, and invested. After the investment had set the blade was withdrawn from the mold and blade-shaped castings were made. These castings were embedded in polyester resin, sectioned perpendicular to the blade edge, examined, and measured under magnification. The width of the cast edge or profile, referred to as the meniscus, was gauged as a measurement of castability.. The authors reported that the gold control alloy consistently cast the finest margin while the non-noble alloys produced a cast edge or meniscus of varying thicknesses. Their study ranked alloys according to margin castability.

Utilizing a blade-shaped pattern described by Mackert et al. (1975), MacNamara et al. (1977) investigated the castability of different alloys and casting machines. They reported that the Whip-Mix Tricaster (pressure/vacuum) and the Whaledent Chronomatic (vacuum/pressure) cast sharper margins than the Jelenko Thermatrol machine (centrifugal force).

The Chayes Virginia Torit 270-B casting machine (centrifugal/vacuum) was included in a follow-up study of Eames and MacNamara (1978) utilizing the same experimental design. A "sharper edge" was produced by the three vacuum casting machines. The authors also concluded that since a 6 pennyweight mass was used for each casting, the density of the alloys tested was not a significant factor in determining castability.

A pattern consisting of four wedges cast simultaneously was used by Nielsen and Shalita (1977). The authors contended that such a pattern could predict the success of casting sharp margins and they described this pattern as a "...powerful tool for measuring the effect of surface tension, metal density, and mold and casting temperature on margin sharpness." High fusing precious alloys filled the margin less completely than Type III "crown and bridge alloys", but a sufficient increase in casting pressure could overcome the liquid metal resiliency.

Barreto, Mumford, and Goldberg (1978) utilized a standardized wedge pattern (4.5 cm long and 1 mm thick tapering to 0.1 mm at the apex) to assess castability. In their study, none of the high fusing non-noble alloys exhibited 100% castability. Decreasing castability was observed from high gold to low gold to non-noble alloys and this trend tended to parallel the decrease in specific gravity of the alloys. The authors concluded that their wedge pattern successfully discriminated among the castabilities of the different alloys. Utilizing the same castability model, Barreto et al. (1980) reported that SMG-II, a high gold alloy, exhibited a superior castability to three non-noble alloys.

The castability of six centrifugally cast dental alloys was evaluated by Pines et al. (1979) with the Nielsen-Shalita model. The authors concluded that marginal filling was influenced by the pressure differential within the mold, reported by Nielsen and Carton (1976), as well as by the liquid metal pressure and surface tension. Sutow et al. (1981) evaluated

the ability of ten non-noble alloys to reproduce the four levels of a thin trapezoidal wedge-shaped pattern.

A double edged razor blade pattern was utilized by Nielsen and Sumithra (1984). They used a 7^{o} edge since this angle was more acute than the angle of the margin on an average dental which they stated was approximately 15^{o}. Their castability pattern possessed a surface to volume ratio of approximately 10:1, compared to a ratio of approximately 1:1 for the an average crown. Castability ranges for the alloys were determined at mold temperatures of 1350^{o}F or less. Nielsen and Penugonda (1985) utilized this test pattern in evaluating eight different investments.

3. Comparison Of Castability Patterns And Experimental Designs.

Eight castability patterns were evaluated by Agarwald and Ingersol (1982). They examined the following patterns: a spiral wax pattern, a single crown coping, a polyester mesh screen, a Nielsen "casting monitor", a 28 gauge wax plate, a knife-edged wedge pattern, a segmented disc, and a three unit fixed partial denture. These eight patterns were connected to a single sprue with eight spokes. The casting ring's position was varied so that each pattern was cast in all quadrants during the experiment. The authors concluded that the polyester mesh pattern provided a predictable measure of castability and that the Nielsen castability model provided maximum information concerning casting conditions.

E. Sprue Geometry and Placement

In regards to sprue design, Preston and Berger (1977) said it best: "Spruing is an art which is not well understood and practiced. The last word has not been written on sprue design and pattern position".

As early as 1919, Volland pointed out the importance of sprue design when he stated that "a reasonably sized sprue wire is necessary" to obtain a sound casting. Volland utilized a Victrola needle in his casting technique. A short thick sprue was recommended by Maves (1928). He stated that such a sprue allowed for more molten gold to enter the casting, which resulted in a denser casting with less shrinkage.

The significance of the sprue has not been appreciated by every author. Rice (1929) reported that the size, shape, and placement of a sprue was a personal preference and stated that the "location of the sprue is of

little relative importance". Asher and Comstock (1933) disagreed with Rice's belief. They evaluated many castings and identified a definite "zone of weakness" in the area of the sprue. The authors recommended placing sprues in areas which could be readily cleaned and were without stress and strains, due to the porosity they observed in the sprue area.

1. Sprue Position.

Phillips (1932) advocated attaching the sprue to the marginal ridge on the wax pattern for an MOD inlay in order to obtain a suitable casting. The importance of utilizing a short, large diameter sprue attached to the greatest bulk of the wax pattern was recognized by Sturdevant (1938) and Crawford (1940). Such placement provided molten alloy around the dendrites of the solidifying casting, which reduced porosity around the base of the sprue. Two sprue methods were advocated by Wilson (1941) to avoid shrinkage porosity during solidification. The first was a short large sprue (5mm long and 12 to 14 gauge). The second sprue was a "medium size" sprue with a wax reservoir about 1/16" from the wax pattern. This reservoir allowed the casting to solidify first followed by the sprue and then the reservoir. Keys (1945) agreed that a reservoir reduced porosity; however, he felt it was difficult to place the reservoir close enough without damaging the wax pattern.

In addition to shrinkage porosity, Brumfield (1950) demonstrated that the rate at which mold gases were displaced was affected by the location and size of the sprue system. A fundamental problem in casting complete crowns was identified as the elimination of mold gases during the casting procedure. A 10 gauge wax vent placed 1/16 to 1/8" from the internal aspect of the occlusal surface was evaluated by the author and resulted in satisfactory castings.

A reservoir larger than the inlay being cast was advocated by Markley (1953) in order to minimize shrinkage porosity. He utilized sprues of variable length to position the wax pattern approximately 1/4" from the end of the ring to reduce porosity from occluded gases. To provide an escape for mold gases, Blanchard (1953) attached vents to the wax pattern at the sprue junction. Plastic-fibered whisk broom straw was heated, molded to the desired shape, and attached to the periphery of the crucible former. A similar sprue-vent system was examined by Wight et al. (1980) while casting non-precious alloys. Their investigation utilized a

rectangular sprue with a flared attachment with vents from the sprue attachment areas. The vented castings were more "defect-free" than the non-vented castings. A vent and its influence on the elimination of gases during casting was evaluated with microthermocouple analysis by Rawson, Gregory, and Lund (1972). The vent registered 325°F lower than the body of the casting during solidification. The authors hypothesized that the vent served as a "chill set" for rapid heat elimination from the casting and a focus for solidification.

2. Sprue Length And Diameter.

Many investigators have reported on proper length and diameter of the sprue. After evaluating castings made utilizing 3 mm long sprues of 10, 14, and 18 gauge, Fairhurst, Kozak, and Ryge (1955) reported that only those castings made with a 10 gauge sprue were free of porosity. Peyton, Mahler, and Asgar (1956) found that an excessively long sprue resulted in shrinkage porosity and that a sprue of excessively large diameter allowed the mold to be filled so rapidly that escape of gases through the investment was prevented. They recommended a sprue length of 3 to 4 mm, while varying the diameter of the sprue from 18 to 24 gauge depending on the mass of the casting. The effect of sprue length on subsurface porosity was studied by Ryge et al. (1957). They concluded that the sprue diameter should be greater than the largest cross-section of the wax pattern. In addition, they reported that a sprue length of 9 mm prevented molten gold alloy from entering the mold too rapidly, resulting in "subsurface porosity".

The effect of 25 different casting variables on "back pressure" porosity was evaluated by Strickland and Sturdevant (1959). After 328 castings, the authors did not find a correlation between sprue length, gauge, or the angle of sprue attachment as long as the pattern was positioned 1/4" from the end of the investment. However, they found that a small diameter sprue resulted in "suck back" porosity at the sprue attachment area. Sausen and Serr (1958) stated that an excessive emphasis had been placed on utilizing a "short thick sprue", and that a sprue could be 10 mm long if the diameter was sufficient. Everyone did not agree with their assessment. Leinfelder et al. (1963) supported the work of Ryge et al. (1957) when they stated that the diameter of the sprue was the crucial factor in preventing localized shrinkage porosity. Based on

empirical laboratory observations, Alleluia (1980a) recommended using a longer sprue for high gold high density alloys and a shorter sprue for lower density alloys.

3. Sprue Attachment To The Wax Pattern.

The earliest report concerning sprue attachment was by Sturdevant (1938) who recommended placing the sprue pin on the largest bulk of wax, usually the marginal ridge on MOD inlays. In order to reduce porosity, Shell (1925) and Thayer et al. (1963) recommended using the fewest number of possible sprues. Crawford (1940) described a straight "short thick" sprue which was widely used at the time.

The first to mention flaring of the sprue was Asgar and Peyton (1959). They originally stated that a "flaring" should occur at the sprue/wax pattern junction and they postulated that "flaring of the sprue may act in the same way as placing a reservoir very close to the wax pattern, and/or it may facilitate the flow of molten gold into the cavity". Regardless of the mechanism, the authors demonstrated that a flared sprue attachment eliminated the porosity occuring on the inner surface of gold castings. This opinion did not reach a consensus. After investigating 23 casting variables affecting porosity, Strickland and Sturdevant (1959) reported that "adding a bulk of wax at the site of the sprue attachment did not alter the occurrence of porosity".

Tuccillo and Nielsen (1964a) believed that flaring was necessary "... for minimizing both investment debris and possibly aspirated air". Tuccillo and Nielsen (1964b) observed: "Some technicians add to this minimal flaring a further filleting, thus making a heavy fillet, on the theory that the molten metal should flow in smooth paths". They further stated: "The degree of filleting has not been established by research work, and technicians disagree on this point".

For high fusing ceramo-metal alloys Nielsen and Ollerman (1976) reported that flaring the sprue attachment was needed in order to obtain a structurally sound casting. When a straight sprue was used, the high fusing molten alloy hit the mold wall and raised the temperature in a localized spot on the interior surface of the mold, which then contributed to "suck back" porosity. The authors agreed with Asgar and Peyton (1959) in recommending to "... spread the molten metal heat over an increased area by flaring the sprue...".

To enhance margin castability, Craig (1985) suggested that the sprue should be directed toward the fine margins of the wax pattern. In order to minimize turbulence in the molten alloy and to decrease porosity at the sprue/wax pattern junction, Craig also recommended flaring the sprue at the point of attachment which allowed for an even flow of metal into the mold.

McLean (1980) recognized: "The design of the sprue channel leading from the crucible to the mould cavity makes a vital contribution to the success of the casting". Utilizing observational laboratory studies on casting completeness, McLean recommended large diameter sprues (3.5 mm) that tapered down to a cone of one-half that diameter (1.75 mm) at the point of attachment to the wax pattern. This constricted sprue attachment was obtained by softening the end of the sprue rod and rolling it between the fingers to form a cone. McLean's results directly contradicted the findings of Nielsen and Ollerman (1976) and Asgar and Peyton (1959) regarding a flared attachment design to prevent "suckback porosity".

Others have advocated the constricted sprue technique. Rousseau (1984) described a casting method that utilized a constricted sprue similar to McLean's. Rousseau contended that the "tapered" sprue prevented porosity at the sprue junction of the casting. Engleman and Blechner (1981) suggested that an increase in velocity of the molten alloy entering the mold space elevated the density of the casting. They recommended using a constricted sprue which would "... create a nozzle effect as the molten alloy pours through the sprue into the wax empty chamber". Grunberg and Lutz (1985) theorized that their sprue design was responsible for "... creating a Venturi effect at the point of entry". They suggested constricted sprues that were fabricated by rolling the sprue between the fingers at the end at the point of attachment to the pattern.

A sprue that was attached to the wax pattern at the thickest portion without flaring or tapering was recommended by Wagner (1980). A straight sprue was also advocated by Sperner and Bramer (1982b). They suggested that a sprue be attached to the wax pattern without flaring for "precious metal porcelain veneer alloys". They reported that a flared attachment caused void formation; however, they did not offer an explanation nor did they postulate on a mechanism of such formation.

Compagni, Faucher, and Yuodelis (1984) stated that sprue design was more critical than the type of casting machine or heat source. They investigated the effects of five sprue designs, casting machines, and heat sources on casting porosity. The authors found the greatest amount of casting porosity with McLean's bottleneck-constriction and concluded that constrictions should not be utilized with straight sprues.

Rieger, Tanquist, and Vainer (1986) utilized a conical shaped sprue to evaluate the castability of a base metal alloy. They reported that their conical shaped sprue produced more complete castings than did the control straight sprue.

In a well-controlled study Verrett and Duke (1989) demonstrated that with a gold-palladium alloy both straight and flared sprues resulted in significantly less porosity than either abrupt or gradual constricted sprues in the area of sprue/casting junction. He also demonstrated better castability of this alloy when either a straight or a flared sprue was utilized.

F. Palladium-Silver Alloys

The palladium-silver alloy became available to the dental profession in 1973, with the introduction of Cameo-Lite (J.F. Jelenko & Co., Inc.). A year later, Will-Ceram W-1 (Williams Dental Co., Inc.) became the first palladium-silver alloy to be granted a United States patent. The palladium-silver alloys are palladium based and designed for metal ceramic applications. They are composed of 50-60% palladium and 30-40% silver with a balance of tin and/or indium and other trace elements (Moffa 1983, Bertolotti 1984, and Naylor 1986). Goodacre (1989) has reported that the palladium-silver alloys constitute a fairly significant portion of the noble metal ceramic alloy sales market in North America.

Some confusion about the palladium-silver alloy group has occurred in the literature due to a lack of standardized terminology. The terms palladium-silver and silver-palladium have been mistakenly interchanged. McLean (1979) stated that the palladium-silver alloys did not cast very well. However, this statement was based on a study using silver-palladium alloys (Nitkin and Asgar 1976). The silver-palladium alloys are silver based, designed for nonceramic applications, and have their own specific handling characteristics. The reader must carefully evaluate the

composition of the alloy to determine if a palladium-silver alloy is being discussed.

In his status report on palladium-silver alloys, Huget (1974) discussed the potential problems of castability and fit and porcelain discoloration due to high silver content and mentioned the need for additional research. Tuccillo (1977) reported that palladium-silver alloys handled as well as gold-palladium and gold-platinum-palladium alloys. As previously mentioned, McLean (1979), referencing a study that evaluated silver-palladium alloys (Nitkin and Asgar 1976), reported that palladium-silver alloys were hard to cast and fine margins were difficult to reproduce.

In a study used to evaluate a new castability mold composed of sprue wax and six different gauges of nylon fishing line, Howard, Newman, and Nunez (1980) ranked a palladium-silver alloy last in castability. However, this alloy was not statistically different from the other six alloys tested. In 1982, Myers and Cruickshanks-Boyd used a vacuum-pressure casting machine to evaluate the castability and marginal fit of a palladium-silver alloy. They reported that it was an acceptable alternative to gold-containing alloys. In addition, they concluded that the reason for the difference between their findings and those of Howard et al. was the result of a more accurate monitoring of alloy temperature.

Bertolotti (1983) reported on the excellent working characteristics of the palladium-silver alloys. Hinman et al. (1985) reported on the castability of eighteen metal ceramic alloys. They established castability values by counting the number of squares which were successfully cast in a polyester sieve cloth mold. The palladium-silver alloy that they tested placed fourth from the last (15th out of 18) in a rank ordering. Naylor (1986) stated that the palladium-silver alloys melted and cast as easily as the gold-base metal ceramic alloys, while casting margins completely.

An incident of subsurface porosity in an induction-melt of a palladium-silver alloy at the Veterans Administration's Central Dental Laboratories was reported by Reisbick (1985). This porosity was apparently related to overheating of the alloy. The various aspects for the proper handling of palladium-based alloys were described by Resnick (1985). He stressed the importance of proper torch adjustment and stated that overheating the alloy or the use of excess oxygen could result in

bubbles, blisters, or voids. The use of a noncarbon phosphate-bound investment was also advocated by Resnick in order to prevent carbon embrittlement. Naylor (1986) reiterated the importance of proper torch adjustment and recommended that carbon crucibles not be used with the palladium-silver alloys.

Three high-palladium alloys were melted and cast utilizing graphite crucibles in order to induce carbon impurities by Hero and Syverud (1985). The palladium-silver alloy was only slightly carbon enriched, but the two high-palladium alloys, with no silver, had incorporated greater amounts of carbon impurities. The carbon uptake resulted in a considerable reduction of ductility and metal ceramic bond strength in the two high-palladium alloys, but had no negative effect in the palladium-silver alloy.

G. Base-Metal Alloys.

In general, base metal alloys are platinum colored, lightweight, and possess either minimal or no scrap value. They contain no gold, silver, platinum, or palladium. Naylor and Young (1985) stated that "when used in the literature, base metal should be interpreted as a term synonymous with non-precious". Compared to Type IV gold alloys in removable partial dentures, base metal alloys (both cobalt-based and nickel-based) feature lower cost, lower density, greater stiffness, greater hardness, and comparable clinical resistance to tarnish and corrosion. (Anusavice 1985)

The first cobalt-chromium alloys were developed in the early 1900's by Elwood Haynes, a pioneer automobile manufacturer. He called the alloys "stellite" due to their bright, lustrous, hard, strong, and nontarnishing qualities and these alloys became known as "Haynes stellites". In 1929, Erdle and Prange developed a suitable casting technique for one of these high melting alloys and made the first dental castings utilizing a cobalt-chromium alloy. That alloy or stellite is now commonly known as Vitallium. A few years later, nickel-chromium and nickel-cobalt-chromium alloys were introduced. In these systems, cobalt and nickel are almost interchangeable. As nickel replaces cobalt, the alloy's strength, hardness, modulus of elasticity, and fusion temperature tend to decline while its' ductility may increase. (Phillips 1973; Craig 1985)

Base metal alloys have been widely accepted for the fabrication of removable partial dentures for nearly sixty years. The significant increase in the cost of gold and other noble metals during the 1970's lead to an increase use of base metal alloys in fixed prosthodontics. Haskel (1982) surveyed 1,000 dental laboratory owners concerning alloys utilized in fixed prosthodontics. He reported that in 1978 only 29% used a base metal alloy for metal ceramic restorations; however, by 1981 70% were utilizing base metal alloys for fixed restorations.

Nickel and cobalt are the primary metals in commercially available alloys used in fixed restorations. The next most predominant metal is chromium, which increases the alloy's resistance to oxidation and assists in solid solution hardening. Minor elements have more effect on the physical properties of an alloy than does the relative nickel-cobalt-chromium concentration. Generally these minor elements are utilized to improve casting and handling characteristics, corrosion resistance, and porcelain bonding ability. One of the more important additions is silicon, which imparts good casting properties to nickel alloys and increases its' ductility. Beryllium enhances the casting of nickel alloys to high tolerances by perhaps acting by helping to keep the metals alloyed during casting process. (Everhart 1971; Phillips 1973; Kelley & Rose 1983)

The majority of nickel-chromium alloys used for fixed prosthodontics contain the following by weight percentages: 61-81% nickel. 11-27% chromium, and 2-14% molybdenum. The cobalt-chromium alloys utilized in fixed restorations contain the following by weight percentages: 53-67% cobalt, 25-32% chromium, and 2-6% molybdenum. Many other elements can be added in small percentages to these alloys and they are aluminum, beryllium, boron, carbon, cobalt, copper, cerium, gallium, iron, manganese, niobium, silicon, tin, titanium, and zirconium. (Anusavice 1985)

Earnshaw (1958) evaluated casting shrinkage of five alloys available in Great Britain. He found that there was no difference between torch and induction melting. In addition, he reported an actual casting shrinkage of 2.2% and recommended a mold expansion of 2.25% for accurate compensation. Anderson (1972) warned that base metal ceramic alloys were difficult to cast with accuracy, particularly in thin sections. Moffa and Jenkins (1974) in their status report on base metal alloys reported that the overall manipulation of base metal alloys to be significantly

different from that for conventional gold-based alloys. They suggested that the manufacturer's recommendations be followed explicitly to minimize technique sensitivity.

Nitkin and Asgar (1976) evaluated alternative alloys to Type III gold utilized in fixed prosthodontics. In terms of fit, they reported that the nonprecious castings, including those made from two nickel-chromium alloys, were inferior to castings made from precious and semiprecious alloys. They stated that an improved investment capable of higher expansion was needed to obtain better casting results with base metal alloys. In addition, the authors recommended the use of the indirect spruing to decrease suckback porosity caused by premature solidification of the alloy.

Several other authors have investigated the casting accuracy of base metal alloys. Younis (1977) reported that the fit of base metal alloys was greatly improved by utilizing a double asbestos liner, indirect spruing, and an extra wind of the casting machine. Smith et al. (1977) demonstrated improved fit of castings from nonprecious alloys by adjusting the liquid-water ratio for phosphate bonded investments and by increasing the burnout temperature from 1300°F to 1500°F. Marbie et al. (1980) reported that the use of sufficiently high investment burnout temperatures produced base metal castings which fit. Kuffler et al. (1981) studied the casting accuracy of base metal alloys and suggested modification of investment materials and/or techniques to enhance the fit of cast base metal restorations. Duncan (1982) evaluated casting accuracy of nickel-chromium alloys and reported that the four nickel-chromium alloys tested did not cast as consistently or as accurately as a precious alloy (Jelenko "O"). The author suggested further research to determine the correct expansion compensation of selected investments. Vermilyea et al. (1983) evaluated the effect of investment material on casting accuracy of five base metal alloys and they suggested alternation of investment manufacturers' recommended techniques to enhance the fit of base metal restorations.

Asgar and Arfaei (1977) reported that the casting machine had the greatest influence on castability, with the type of alloy utilized being the second determining factor. Barreto, Mumford, and Goldberg (1978) demonstrated that the type of investment utilized affected the castability

of base metal alloys. The investment burnout procedure was reported to affect the castability of base metal alloys by Barreto, Goldberg, Nitkin, and Mumford (1979).

Vincent, Stevens, and Basford (1977) compared the castability of a nonprecious alloy with two precious metal alloys. The authors concluded that the variability in results was related to density; and they suggested that the problems caused by low density could be resolved by increasing the casting force. Eden et al. (1979) demonstrated that a linear relationship existed between melting temperature range and the amount of casting undersize. Cole and Vincent (1980) reported that casting two non-precious alloys in standard metal casting rings produced undersized castings. They recommended wax paper casting rings to allow for proper expansion of the casting investment; this procedure yielded a more accurate finished casting.

Wright et al. (1980) evaluated three variables affecting the casting of base metal alloys: venting, sprue width, and thickness of investment covering the end of the pattern. The authors reported that venting with sprue widths of 2 mm or more eliminated voids and porosity, while varying the thickness of investment above the pattern had no effect on casting results. Thomson (1982) studied the effect of increased mold temperature on the casting ability of three nonprecious alloys and concluded that if nonprecious alloys are to be used successfully in restorative dentistry, further research will be required regarding techniques and materials used in the manipulation of these alloys. Moffa et al. (1984) in a 5-year clinical study determined that there were no significant differences in the clinical performance of a base metal alloy (Verabond) and the control gold alloy (Jelenko "O").

Covington et al. (1985) evaluated the castability of 32 different base metal and semiprecious alloys. They reported that the nickel-beryllium base metal alloy group exhibited the best percentage of casting completeness (mean 99.5%) followed by the silver-palladium group (mean 92.3%), the palladium group (mean 83.6%), the nickel-chromium group (mean 81.3%), and the chromium-cobalt group (mean 74.4%). The authors theorized that the positive effect on castability demonstrated by beryllium was due to the small size of its atom, which probably contributed a property not unlike a lubricant while the alloy was in the molten state. In

addition, the authors stated that perhaps the single most important element in uniformly producing high values of castability was the induction heating and melting of alloys. Torch melting tended to overheat the base metal alloys, which could result in a burning off minor constituents that are responsible for many properties of these alloys.

Hinman et al. (1985) utilized a Number 18 polyester sieve cloth and five brands of phosphate bonded investment in evaluating the casting behavior of 18 high-fusing dental casting alloys. The percentage of completely cast segments determined the "castability value" for each alloy. The authors reported that three base metal alloys, two nickel-chromium and one cobalt-chromium, demonstrated higher castability values than a gold-platinum-palladium alloy (Jelenko "O"). In addition, they concluded: the brand of investment used can produce a significant effect on castability with some alloys; castability value increases as mold and casting temperature increase; each alloy demonstrated an optimal mold and casting temperature above which castability did not improve; and the effect of mold temperature on castability is substantial for some alloys and less significant for others.

Rieger, Tanquist, and Vainer (1986) evaluated the effects of a conical sprue on the castability of a base metal alloy. The authors concluded that base metal alloys require casting techniques specifically designed for their physical properties and that for the base metal alloy tested their conical sprue produced more complete castings.

III. METHODS AND MATERIALS

The effects of four different sprue designs on porosity and castability were investigated. The variable studied was limited to the configuration of the sprue attachment. Based on recommendations found in the literature, the following types of sprue attachment designs were studied: gradual constricted, abrupt constricted, flared, and straight.

Standardized complete crown shaped wax patterns were cast and examined utilizing a technique similar to Eames and MacNamara (1978), Bessing (1986), and Verrett and Duke (1989). Fifteen samples of each of the four different sprue attachment designs were cast with three dental casting alloys of different specific gravity. The alloys studied were:

1) Firmilay (J.F. Jelenko & Co., Armonk, NY), a Type III gold alloy with specific gravity of 15.5 gm/cc containing 74.5% gold, 3.5% palladium, 11% silver, 10.5% copper, and a trace amount of zinc;

2) Jel-5 (J.F. Jelenko & Co., Armonk, NY), a palladium-silver dental alloy with specific gravity of 10.7 gm/cc containing 54% palladium, 38.5% silver, 7% tin, and 0.5% gallium;

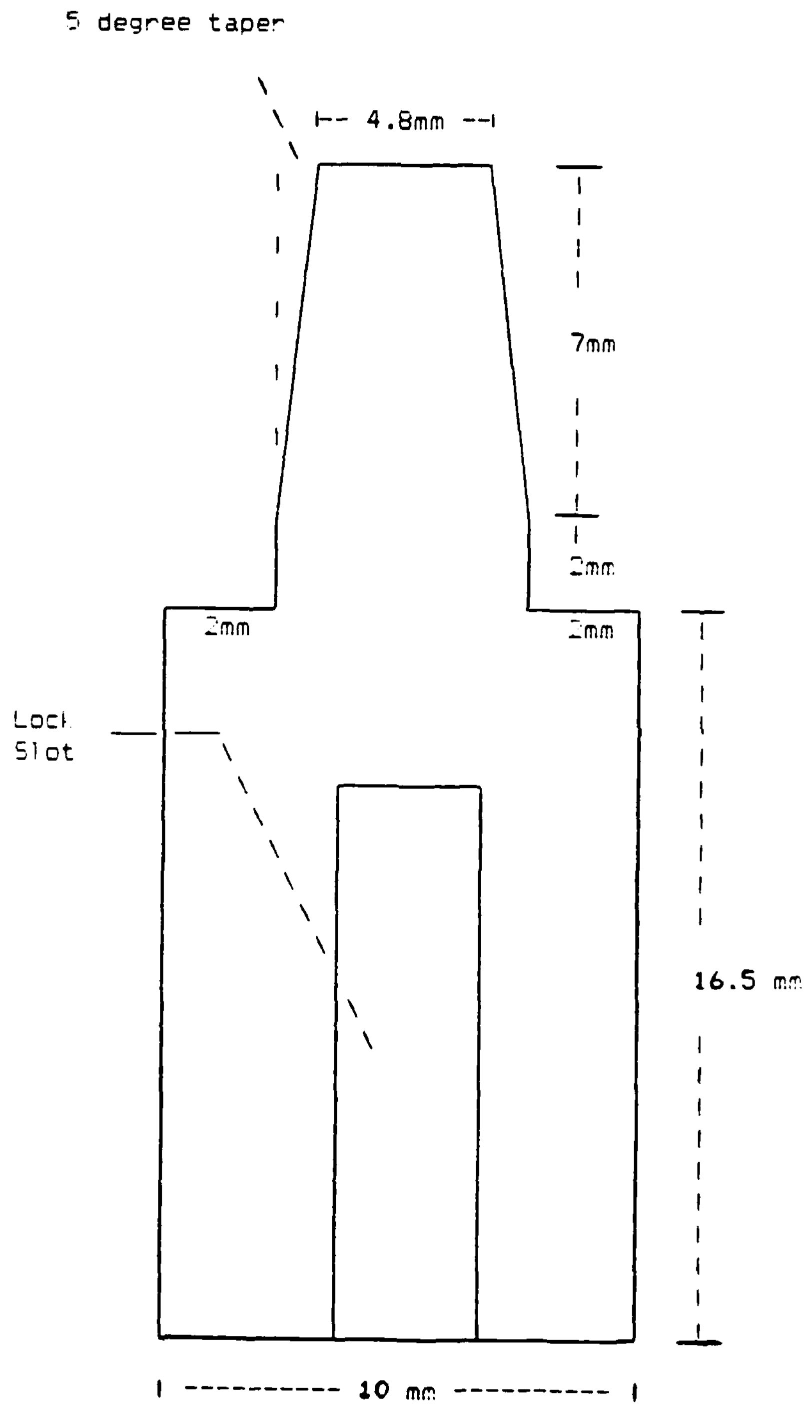
3) Rexillium III (Rx Jeneric Gold Co., Wallingford, CT), a base-metal dental alloy with specific gravity of 7.75 gm/cc containing 74-78% nickel, 12-15% chromium, 4-6% molybdenum, and 1.8% (maximum) beryllium.

A. Fabrication of Standardized Wax Patterns

1. Master die.

A master die was machined from plexiglass (Drew Plastics, Milford, DE) to simulate the preparation for complete premolar crown. Asgar and Peyton (1959) demonstrated that castings of complete premolar crowns exhibited porosity more frequently than other single crown castings, due to increased difficulty in venting gases from the mold space during burnout and casting. This master die was machined to have a crown height of seven mm, an occlusal diameter of five mm, a five degree axial wall taper (ten degree convergence angle) and a knife edge finish line. The occlusal-axial line angle was rounded (Figure 1). The dimensions and

FIGURE 1: Schematic diagram of dimensions of master die.



5 degree taper
4.8mm
7mm
2mm
2mm
2mm
Lock
Slot
16.5 mm
10 mm

taper of the master die were similar to those of Philp and Brukl (1984) and Verrett and Duke (1989).

Utilization of a knife edge finish line allowed for fabrication of a wax coping with wedge shaped axial walls in cross section. Vaidyanathan and Penugonda (1985) reported that wedge shaped castability patterns are more sensitive to castability factors and more reproducible. The resulting minute knife edge wax margins exceeded the castability of each of the three alloys evaluated in this study.

2. Working refractory dies.

Working refractory dies were fabricated by using the indirect impression technique. An addition reaction silicone impression material (President, Coltene, Switzerland) was used to obtain ten impressions of the master die. Custom trays were made utilizing forty-five mm sections of 3/4 inch inside diameter poly-vinyl-chloride tubing. The impression material was retained in the tray via use of internal mechanical retention and adhesive (President Adhesive, Coltene, Switzerland). A surface tension reducing agent was employed prior to pouring the investment material.

One hundred eighty working dies were obtained (sixty for each alloy studied) by pouring up each of the master impressions eighteen times in a phosphate bonded refractory investment material (DVP, Whip Mix Corp., Louisville, KY). Fifty grams of DVP was hand spatulated in nine ml of distilled water for fifteen seconds in a vacuum mixing bowl and then vacuum mixed at 425 RPM for thirty seconds (Vacuspat, Whip Mix Corp., Louisville, KY). The working refractory dies were separated from the impressions after two hours utilizing a stream of compressed air.

3. Wax patterns.

The knife edge margin of the working refractory die was identified and marked with a red wax pencil utilizing 10X magnification (EMT-Widefield Stereo Microscope, Meiji-Labax Co., LTD., Tokyo, Japan). A thin layer of hard inlay wax (Dr. Peck's Improved Inlay Wax, Interstate Dental Co. Inc., Freeport, NY) was intimately adapted to just beyond the finish line on the working refractory die via an electric waxing device (Micro-Matic, belle de st. claire, Van Nuys, CA). The remaining bulk of the waxup was made by dipping the refractory die in molten inlay wax (Maves Inlay Wax, Maves Co., Cleveland, OH) in an electric wax dipping pot (Dura Dip Wax

Unit, belle de st. claire, Van Nuys, CA) until a uniform bulk of excess wax covered the die.

A commonly used technique for the evaluation of castability has been to cast prepared standardized patterns. In order to obtain standardized wax patterns the specially designed sculpturing device (Plate 1) as described by Philp and Brukl (1984) and employed by Verrett and Duke (1989) was utilized. The working refractory dies with their uniform excess waxups were secured in the base of the sculpturing device in a standardized fashion. The base of the die was positioned flush with the base of the device and with the lock slot facing the set screw. The die was then secured in place by tightening the set screw.

A machined movable vertical blade template was then used to sculpture identical wax patterns on each of the one hundred and eighty working refractory dies. As the vertical template was slowly rotated, wax was gently shaved from the excess bulk buildup while the screw attaching the template was gradually tightened (Plate 2). The template was rotated until contact was made with the working refractory die immediately below the finish line marked in red. The resulting margin of the wax pattern was precisely carved to a knife edge on the working refractory die (Plate 2).

4. Sprue designs.

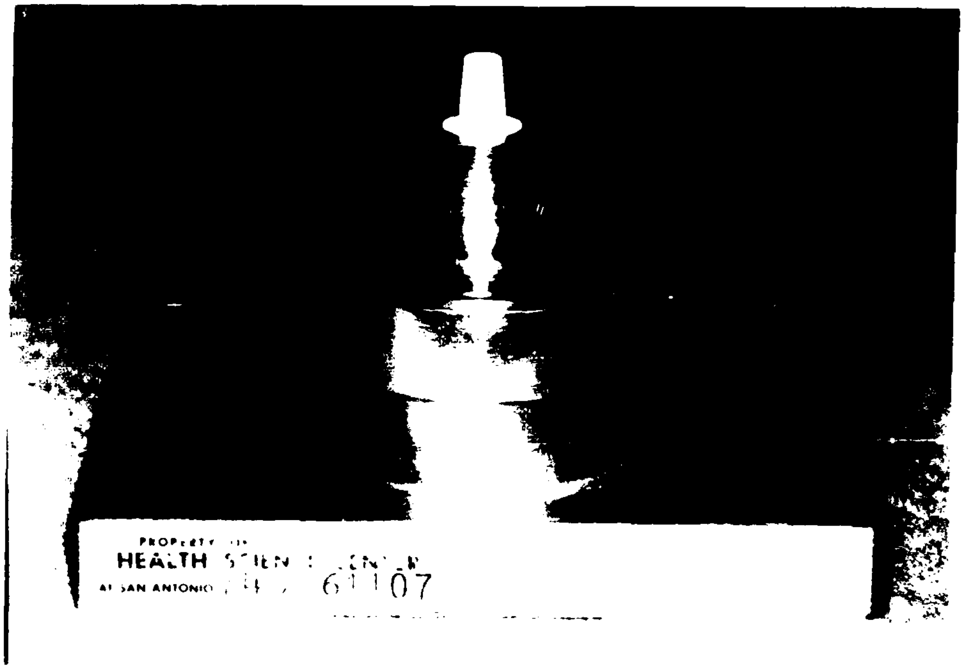
The four sprue designs evaluated were: gradual constricted, abrupt constricted, flared, and straight. A ten gauge (2.6 mm diameter) master sprue pattern was machined from an aluminum alloy for each of the four sprue designs (Figure 2). These metal master sprues were duplicated via a jeweler's wax injection technique until forty-five identical wax sprues of each sprue design were obtained.

The gradual constricted metal master sprue was machined so that its' 2.6 mm diameter constricted down to a 1.3 mm diameter over a distance of 2.6 mm. The abrupt constricted metal master sprue was machined following the recommendations of McLean (1980). The 2.6 mm diameter of the sprue was constricted down to a 1.3 mm diameter over a distance of 1.3 mm. A projection was machined in the center of the superior surface of both the gradual constricted and abrupt constricted master sprues. This projection served as a guide to center the sprue over the occlusal-axial line angle and was 0.5 mm in both width and height.

Plate 1: Sculpturing Device

A. Sculpturing device with refractory working die secured in the base.

B. Sculpturing device with working refractory die and revolving vertical blade template secured into position. Template revolved symetrically around refractory working die.


PROPERTY OF
HEALTH
AT SAN ANTONIO
61107

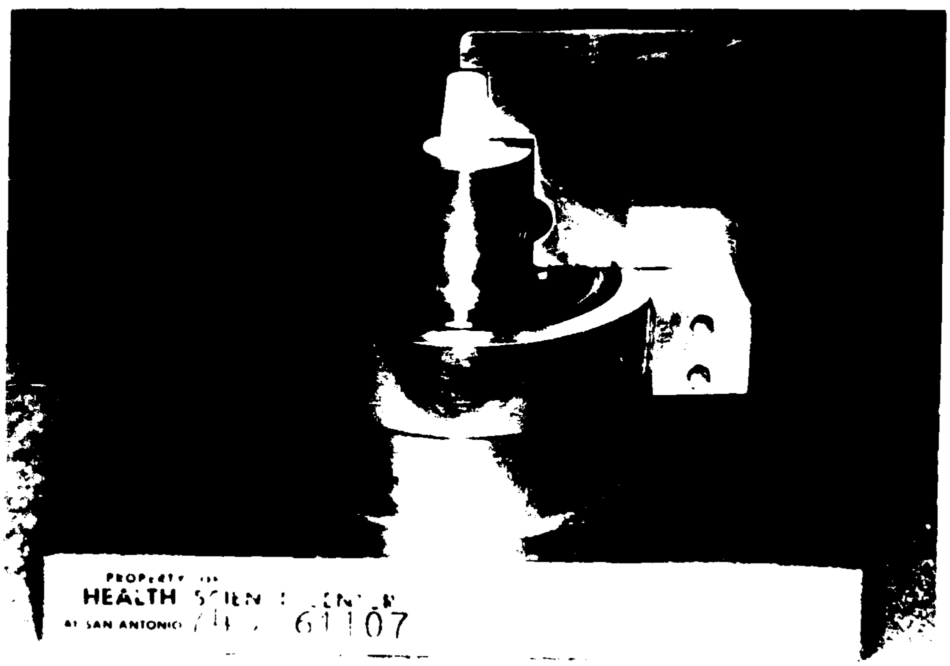

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Plate 2a Wax Pattern Preparation

Vertical blade template was gradually tightened while being revolved around die, resulting in a symetrical shaving of wax.

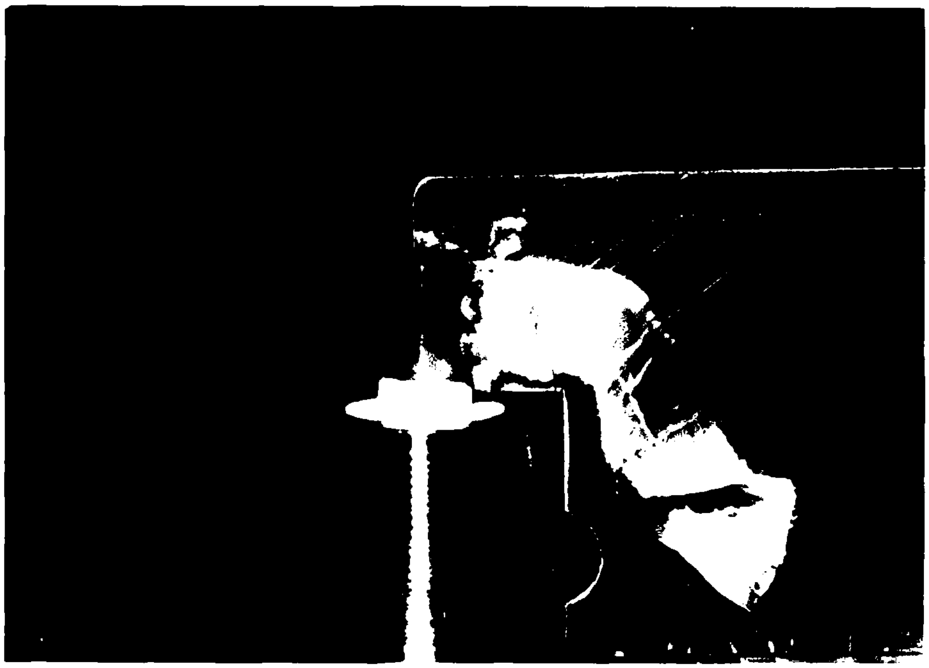


Plate 2b Wax Pattern Preparation

Completed wax pattern. (Note knife edge margin)

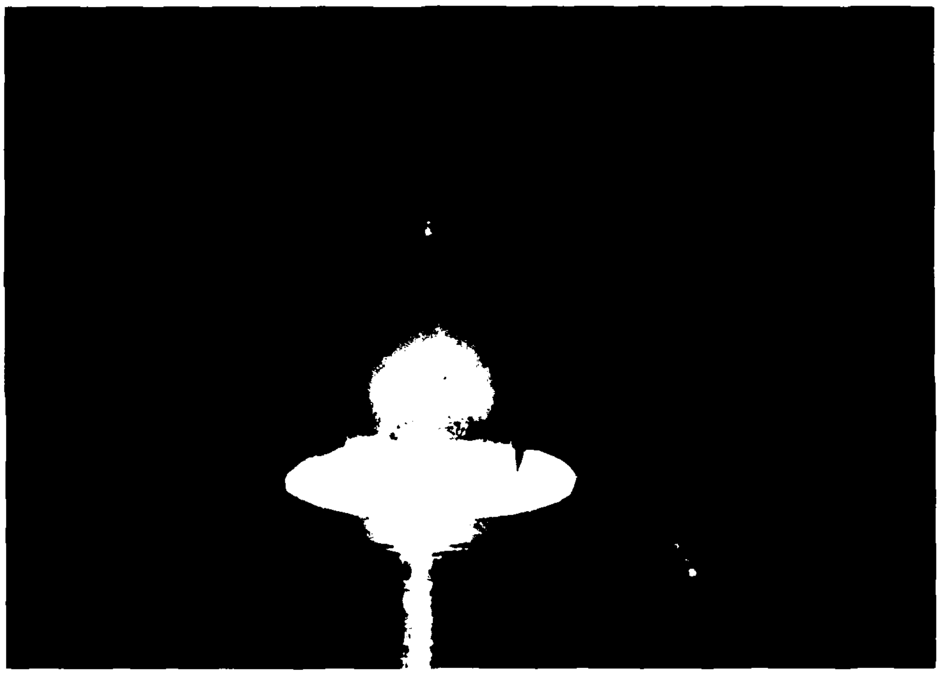
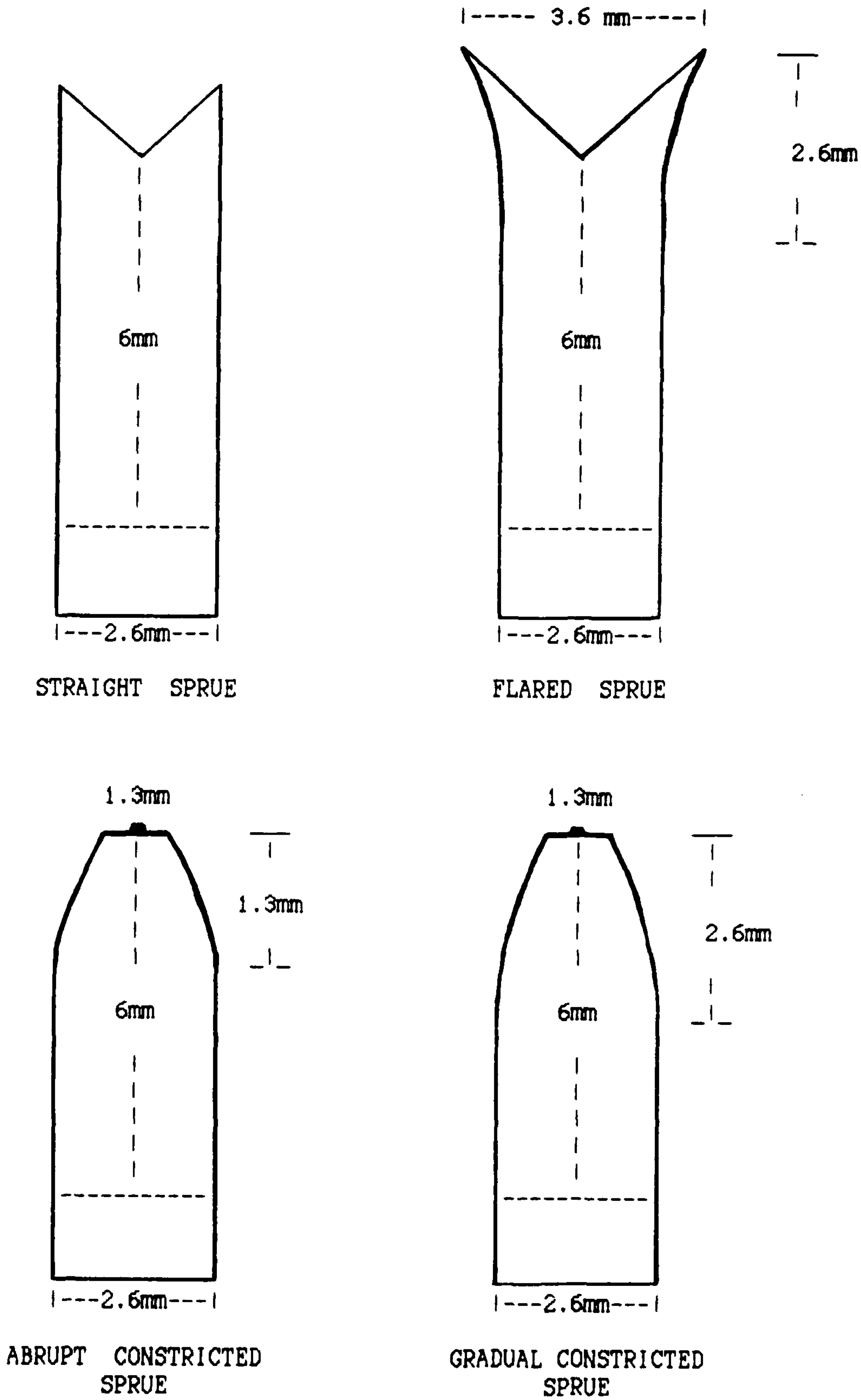


FIGURE 2: Schematic diagram of dimensions of sprue attachment designs.



6mm
2.6mm
STRAIGHT SPRUE
3.6 mm
2.6mm
6mm
2.6mm
FLARED SPRUE
1.3mm
1.3mm
6mm
2.6mm
ABRUPT CONSTRICTED SPRUE
1.3mm
2.6mm
6mm
2.6mm
GRADUAL CONSTRICTED SPRUE

The flared metal master sprue was machined so that its' 2.6 mm diameter increased to 3.6 mm over a distance of 2 mm from the sprue/wax pattern junction. The straight metal master sprue was machined with a uniform diameter of 2.6 mm throughout its' length. A "V"-shaped notch was machined in the superior surface of both the flared and the straight master sprues. This notch served as a guide to center the sprue over the occlusal-axial line angle.

A small scribed line was placed on all four metal master sprues to serve as a positioning guide and to standardize the length of the sprues during investing. This scribed line was machined on the metal master sprues at a distance of 6 mm from the sprue/wax pattern junction.

B. Sprue Attachment

A working refractory die with the completed wax pattern was resecured in the base of the sculpturing device by aligning and tightening the set screw. This assembly was then secured in a survey table (Ney Surveyor, J.M. Ney Co., Bloomfield, CT) which was then secured in the cast holding base of a parallelometer (Royal E.M. Parallelometer, Bell International, Burlingame, CA). The tilt was adjusted until the long axis of the working refractory die was positioned at 135 degrees from the vertical surveyor arm of the parallelometer.

By merely securing a completed wax pattern/working refractory die assembly in the sculpturing device via tightening of the set screw, the angle of sprue attachment to wax pattern was standardized at 135 degrees for each test sample. Each individual wax sprue was gently held in the vertical surveyor arm of the parallelometer by lightly tightening the chuck until slight resistance was felt. The wax sprue was then lowered, centered, and positioned into contact with occlusal-axial line angle of the wax pattern. The sprue was then carefully luted to the wax pattern with a small increment of molten sticky wax (Sticky Wax, J.F. Jelenko & Co., Armonk, NY) utilizing an electric waxer (Micro-Matic, belle de st. claire, Van Nuys, CA).

After releasing pressure from the surveyor's arm chuck, the working refractory die/wax pattern/sprue assembly was removed from the sculpturing device. The junction between the sprue and the wax pattern was refined under 10X magnification (EMT-Widefield Stereo Microscope,

Meiji-Labax Co., Ltd., Tokyo, Japan). A thin separating disk was utilized to remove the base of the working refractory die at a level approximately 2 mm below the margin of the wax pattern.

C. Investing and Casting

The refractory die/wax pattern/sprue assembly was luted in position on a custom made cone-shaped crucible former. This crucible former was fabricated with a convex projection of 1.5 mm diameter located at the six o'clock position. Sprue length was standardized at 6 mm by placing the scribed line of the sprue, flush with the superior surface of the crucible former. The margins of all one hundred and eighty wax patterns were oriented in the standardized position of 30 degrees inferior to the horizontal plane (eight o'clock position), in order to place the margins at the trailing edge during the casting process. Dewald (1979) demonstrated that such positioning encouraged maximal gold flow during centrifugal casting and promoted optimal castability. A surface tension reducing agent (Wax Pattern Cleaner, J.F. Jelenko Co., Armonk, NY) was used to clean the wax patterns prior to investing.

Each casting ring (1 1/4 in x 1 3/8 in) was lined with one layer of liner (Ring-Mate, Whip Mix Corp., Louisville, KY for Rexillium III and Jel-5; Ring Liner, Whip Mix Corp., Louisville, KY, for Firmilay), in order to ease the divestment process. A notch was scribed on the external surface of each casting ring with a separating disk. This notch ran the entire length of the ring and was used to standardize ring orientation during the casting process. The ring was immersed in distilled water for one minute, removed, and shaken briefly to remove excess moisture. The ring was placed onto the crucible former with the notch at the twelve o'clock position.

The refractory die/wax pattern/sprue combinations for both the Rexillium III and Jel-5 were invested in a carbon-free phosphate bonded investment material (Hi-Temp, Whip Mix Corp., Louisville, KY). The Hi-Temp was vacuum mixed according to the manufacturer's recommendations and gently flowed into the casting ring utilizing mild vibration. The invested rings were allowed to bench set for sixty minutes.

The refractory die/wax pattern/sprue combinations for Firmilay were invested in a calcium sulfate bonded investment material (Beauty

Cast, Whip Mix Corp., Louisville, KY). The Beauty Cast was vacuum mixed according to the manufacturer's recommendations and gently flowed into the casting ring utilizing mild vibration. The hygroscopic technique was employed and the invested rings were placed in a 100 degrees Fahrenheit water bath for 30 minutes followed by a 30 minute bench set.

The smooth investment surface on the top of each invested ring was scraped in order to improve the venting of gases during burnout and casting. The custom crucible formers were removed and any loose debris was blown away from the sprue opening with compressed air. The invested rings were stored overnight in a humidor and placed in the furnace in a moist condition (Shillingburg 1981 and Phillips 1982).

The invested wax patterns were cast in groups of twelve. Three invested rings from each of the four sprue design groups were placed in a cold oven (Unitek Automatic Dual Temp Burnout Furnace, Unitek Corp., Monrovia, CA). The rings were uniformly spaced and positioned in three rows and the following burnout temperatures were utilized: Rexillium III - 1600 ^{o}F, Jel-5 - 1400 ^{o}F, and Firmilay - 900 ^{o}F. Each of the fifteen casting groups were heat soaked for three hours and forty-five minutes prior to casting.

All castings were made by the principle investigator with the help of two experienced laboratory technicians. The first laboratory technician was responsible for winding the centrifugal casting machine, positioning the alloy, adjusting the torch, observing the melting of the alloy, and releasing casting arm. The second laboratory technician was responsible for placing and removing the heated casting ring in the casting machine cradle. The positioning of the casting rings in the cradle was standardized by consistently placing the rings in the cradle with the notch at the twelve o'clock position.

The principle investigator was responsible for monitoring the temperature of the alloy with an optical pyrometer. He directed the second technician to remove the heated ring from the oven at a standardized alloy temperature for placement in the casting machine cradle. He then directed the first technician to release the casting arm when the alloy reached its' casting temperature.

The Rexillium III and the Jel-5 alloys were melted in their individual preheated quartz crucibles using a propane-oxygen torch (Harris On-Off

Torch, Veriflow Corp., Richmond, CA) and a multiorifice tip. The Firmilay alloy was melted a preheated clay crucible using the same torch but with propane-air combination. The "On/Off" control of the Harris torch allowed the for the melting of the alloy with minimum of variance from the heat source.

All castings were made in the same broken-arm centrifugal force casting machine (Kerr/Centrifugo, Rommulus, MI). To standardize the amount of casting force, four complete winds of the casting arm were used in casting Rexillium III and Jel-5, while three complete winds were used in casting Firmilay. The amount of alloy used to cast each respective test sample was as follows: one new ingot of Rexillium III, four new pennyweights (6.2 grams) of Jel-5, four new pennyweights (6.2 grams) of Firmilay. The amount of Rexillium III was standardized by utilizing only those ingots which weighed 6.6 to 6.8 grams.

In order to evaluate the effect of the experimental variable of sprue attachment design, the casting temperature was monitored and standardized visually with an optical pyrometer ("Hot Shot" Ratio Scope Model ROS-5, Capintec Instr. Inc., Ramsey, NJ). When the alloy reached a temperature that was 150 ^{o}F below its' casting temperature (2390^{o}F for Rexillium III, 2250^{o}F for Jel-5, and 1740^{o}F for Firmilay), the second technician was directed to remove the ring from the oven and position it in the casting cradle. The first technician released the casting arm at the direction of the principle investigator, when the casting temperature (2540^{o}F for Rexillium III, 2400^{o}F for Jel-5, and 1890^{o}F for Firmilay) of the alloy was recorded by the optical pyrometer.

The rings were allowed to bench cool and then divested by hand. After a gross manual cleaning, the castings were lightly air-abraded with 25 micron aluminum oxide abrasive (Ney-Brasive, J.M. Ney Co., Bloomfield, CT) and further cleaned in distilled water in an ultrasonic cleaner. The sprues were sectioned 3 mm from the sprue/crown junction and the castings with their residual sprues attached were numbered in preparation for examination.

D. Examination and Evaluation of Castings

The castings were positioned on a glass slab with the long axis of the remaining portion of the sprue parallel to the glass via a 1.7 mm thick

positioning jig. Such placement allowed for sectioning in a horizontal plane. A small increment of cyanoacrylate (Krazy Glue, Krazy Glue Inc., Itasca, IL) was utilized to affix the castings to the glass surface.

Following removal of the positioning device, a 16 mm long cylinder of polybutyrate tubing with inside diameter of 1/2 inch was centered over each casting. The tubing was sealed to the glass with wax and served as an embedding form. The castings were then embedded in a clear polyester resin (Castin'Craft Liquid Plastic Resin, ETI, Fields Landing, CA).

The embedded castings of Jel-5 and Firmilay were sectioned in a horizontal plane through the center of the sprue with a diamond saw (Isomet 11-1180 Low Speed Saw, Buehler Ltd., Lake Bluff, IL) utilizing a standardized load (125 gm for Jel-5 and 150 gm for Firmilay) and standardized speed of rotation (7 for Jel-5 and 8 for Firmilay). The Rexillium III embedded castings were sectioned in exactly the same fashion; however, a cubic boron nitrite blade was used with a standardized load of 150 gm and standardized speed of rotation of 7. The position of the casting in the Isomet Saw was standardized by securing the embedded sample in the alignment jig 2.9 mm from the base.

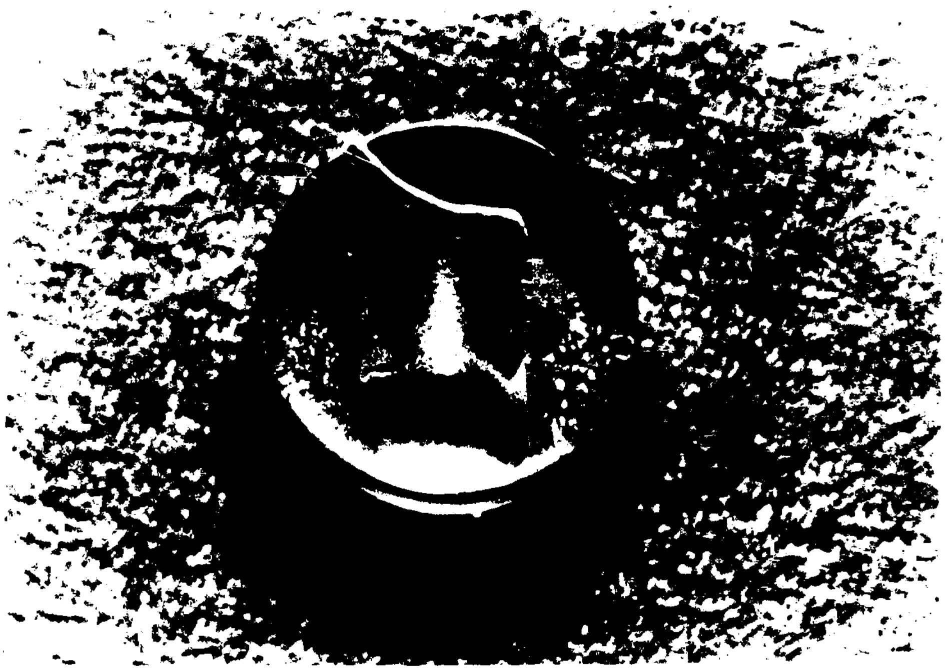
The top half or longer segment of the sectioned embedded casting was metallographically polished using successively finer abrasives. Initial finishing was accomplished with a wet 600 grit silicon carbide paper (Handimet Grinder, Buehler Ltd., Lake Bluff, IL). A six micron diamond polishing paste compound (Polimet, Buehler Ltd., Evanston, IL) on a nylon polishing wheel was used to roughly polish the sectioned castings. The final polishing was accomplished utilizing a 0.05 micron gamma alumina polishing powder on a wet microcloth polishing wheel. This final polish produced a sharp and easily identifiable alloy/resin junction that permitted accurate measurement of the cast margin and facilitated the visualization of porosity within the sectioned plane. (Plate 3)

E. Measurements

The polished surface of each casting was analyzed to determine the influence of sprue attachment design on the castability of the fine margins of the pattern and on the porosity within the casting. All castings were evaluated visually and microscopically. The principal investigator collected and compiled all data.

Plate 3: Polished Embedded Specimen

Embedded specimen sectioned through center of sprue and casting. Polished and ready for subsequent measurements.



1. Porosity.

The quantity of porosity located in the sectioned castings was evaluated utilizing the protocol established by Verrett and Duke (1989). For each of the three alloys studied, a representative subset was selected that contained ten castings from each of the four sprue design test groups. These sectioned castings were photographed in a metallographic light microscope (Zeiss Universal Large Research Microscope, Carl Zeiss Inc., West Germany) with a 35 mm camera (Pentax ES-II, Asahi Optical Co., Ltd., Japan) and 35 mm film (Kodak Panatomic-X, ISO 32, Eastman Kodak Co., Rochester, NY). The section photographed was the sprue-crown junction area of the polished surfaces at a magnification of approximately 50X in the film plane.

For each of the three alloys tested, forty photographs of the sprue-crown junction (five inch by seven inch with a magnification of 225X) were evaluated by four raters. The raters were board-certified prosthodontists. They were instructed to rank order the unidentified photographs in a continuum from the photograph with the least porosity (rank order number 1) to the one with the greatest porosity (rank order number 40). They were also instructed to disregard the following: residual scratches, dust particles, and any artifacts. The rank ordering was accomplished under the same environmental conditions and the raters were not informed about how to differentiate groups in the photographs.

2. Castability.

Castability measurements were recorded for all of the samples utilizing the protocol established by Verrett and Duke (1989). The polished sectioned castings were examined under a microscope (Gaertner Measuring Microscope, Gaertner Scientific Corp., Chicago, IL) to determine the width of the meniscus of the cast margin using a technique similar to Eames and MacNamara (1978) and Bessing (1986), as described by Verrett and Duke (1989). The width of the meniscus was recorded as a measure of castability, i.e. the finer the cast margin, then the better the castability.

The sectioned castings were mounted on a glass slab utilizing a 1/2 inch sphere of modeling clay and a customized paralleling device. The polished surfaces were positioned in a horizontal plane and parallel with thc glass. The glass slab with the mounted sectioned castings was then used as a movable base on the fixed stage of the microscope during the

subsequent measurement of the meniscus of the proximal and distal cast margins.

The Gaertner Measuring Microscope was prepared for use by following these steps:

1. The traveling stage's height was adjusted and securely fixed in position.

2. The fixed and the traveling stages were paralleled to a horizontal orientation.

3. The illuminating lamp was set at 4.5 intensity.

4. The eyepiece focus was adjusted.

Both margins of a sectioned casting were measured three times and the mean of these three values was recorded. This measurement procedure was repeated for each of the one hundred eighty castings (sixty for each of the three alloys studied).

F. Statistical Analysis

The relative porosity values, based on the ranked ordering, and the relative castability measurements, based on the mean widths of the cast meniscus were subjected to statistical analysis.

1. Porosity.

For each of the three alloys investigated, forty photographs of the sprue-crown junction, ten from each of the four sprue attachment design groups, were evaluated and rank ordered by four highly qualified raters. The Spearman Rank Correlation Coefficient test was used to assess interrater reliability. The ordinal level rank order data obtained was analyzed with the Kruskal-Wallis test, a one way analysis of variance by ranks, to determine statistical differences between the sprue design test groups.

The rank of each test group was subjected to analysis with the Mann Whitney U test. This is a nonparametric version of the Two Group Unpaired t-Test utilized to determine statistically significant differences between test groups.

2. Castability.

For each of the three metals studied, a two factor repeated analysis of variance was performed on the means of the proximal and distal meniscus widths from each of the four sprue design test groups to

determine if a significant difference ($p<.05$) existed between the proximal and distal margins meniscus widths, and if a significant difference ($p<.05$) existed between groups. The ANOVA also determined if a significant interaction occurred between the two factors. The Scheffe multiple comparison test was then used to analyze the mean difference between each group.

Specific recommendations for the most appropriate sprue attachment design for each of the three alloys studied can be formulated based upon the statistical analysis of the data collected on porosity and castability.

IV. RESULTS

Fifteen specimens for each of the four experimental sprue attachment designs were cast, embedded, sectioned, polished, and evaluated in the castability portion of the investigation for each of the three dental casting alloys. Ten representative specimens from each of the four experimental sprue attachment designs were photographed and evaluated in the porosity portion of the investigation for each of the three dental casting alloys.

A. Porosity

Results of the Spearman Rank Correlation Coefficient test, utilized to assess interrater reliability of the four independent raters for rank ordering of porosity found in the one hundred twenty photographs (forty for each of the three alloys), are displayed in Table 1. Interrater reliability was found to be highly significant ($p<.001$) among all pairs of raters.

1. Firmilay (a Type III gold alloy).

The Kruskal-Wallis one way analysis of variance by rank revealed a significant difference ($p<.01$) between the four sprue attachment groups with Firmilay (Table 2). The mean rank of each sprue attachment design group for Firmilay is listed in Table 3, and demonstrated diagrammatically in Figure 3. The raw data for rank ordering of percent area porosity on the forty photographs of the sprue-crown junction for Firmilay are listed in the Appendix (Table 22). There were two prominent groupings within the total population of four experimental sprue attachment groups. The mean rank of the Straight sprue attachment group (12.6) and the Flared sprue attachment group (15.5) showed less porosity than the Gradual Constricted attachment. group (mean rank of 26.5) or the Abrupt Constricted attachment group (mean rank of 27.4).

The Mann-Whitney Pairwise Comparison of the test groups for Firmilay (Table 4) revealed that the Straight sprue attachment group ranked significantly less porous than the Gradual Constricted sprue attachment group ($p<.01$) and the Abrupt Constricted sprue attachment

significantly less porous than the Gradual Constricted attachment group ($p<.05$) and the Abrupt Constricted attachment group ($p<.05$). No significant difference in porosity ranking was noted between the Straight attachment group and the Flared attachment group ($p=.44$); and no significant difference in porosity ranking was noted between the Gradual Constricted attachment group and the Abrupt Constricted attachment group ($p=.45$).

The Straight and Flared sprue attachment groups were less porous than the Gradual and Abrupt Constricted sprue attachment groups regarding the sprue-crown junction as evaluated on the forty photographs of Firmilay specimens.

2. Jel-5 (a palladium-silver alloy).

The Kruskal-Wallis one way analysis of variance by rank revealed a significant difference ($p<.057$) between the four sprue attachment groups with Jel-5 (Table 5). The mean porosity rank of each sprue attachment design group for Jel-5 is listed in Table 6, and demonstrated diagrammatically in Figure 4. The raw data for rank ordering of percent area porosity on the forty photographs of the sprue-crown junction for Jel-5 are listed in the Appendix (Table 23). There were three prominent groupings within the total population of four experimental sprue attachment groups. The mean rank of the Straight attachment group (13.6) showed less porosity than the Flared attachment group (mean rank of 20) and the Abrupt Constricted attachment group (mean rank of 20.4), which showed less porosity than the Gradual Constricted attachment group (mean rank of 28).

The Mann-Whitney Pairwise Comparison of the test groups for Jel-5 (Table 7) revealed that the Straight sprue attachment group ranked significantly less porous than the Gradual Constricted sprue attachment group ($p<.01$); and the Flared sprue attachment group was also graded significantly less porous than the Gradual Constricted sprue attachment group ($p<.052$). No significant difference in porosity ranking was noted between the following sets of sprue attachment groups: Straight and Flared ($p=.120$), Straight and Abrupt Constricted ($p=.081$), Flared and Abrupt Constricted ($p=.223$), and Gradual Constricted and Abrupt Constricted ($p=.081$).

The Straight and Flared sprue attachment groups were less porous than the Gradual Constricted sprue attachment group regarding the sprue-crown junction as evaluated on the forty photographs of the Jel-5 specimens.

3. Rexillium III (a base metal alloy).

The Kruskal-Wallis one way analysis of variance by rank revealed that no significant difference ($p=.17$) existed between the four sprue attachment groups with Rexillium III (Table 8). The mean porosity rank of each sprue attachment design group for Rexillium III is listed in Table 9, and demonstrated diagrammatically in Figure 5. The raw data for rank ordering of percent area porosity on the forty photographs of the sprue-crown junction for Rexillium III are listed in the Appendix (Table 24). There were three basic groupings within the total population of four experimental sprue attachment groups. The mean rank of the Straight attachment group (15.6) showed less porosity than the Flared attachment group (mean rank of 18.8) and the Abrupt Constricted attachment group (mean rank of 20.55), which showed less porosity than the Gradual Constricted attachment group (mean rank of 27.05).

The Mann-Whitney Pairwise Comparison of test groups for Rexillium III (Table 10) revealed that the Straight sprue attachment group ranked significantly less porous than the Gradual Constricted sprue attachment group ($p<.05$). In addition, the Flared sprue attachment group was also graded significantly less porous than the Gradual Constricted sprue attachment group ($p<.05$). No significant difference in porosity ranking was found between the following sets of sprue attachment groups: Straight and Flared ($p=.213$), Straight and Gradual Constricted ($p=.172$), Flared and Abrupt Constricted ($p=.352$), and Gradual Constricted and Abrupt Constricted ($p=.099$).

The Straight and Flared sprue attachment groups were less porous than the Gradual Constricted sprue attachment group regarding the sprue-crown junction as evaluated on the forty photographs of Rexillium III specimens.

B. Castability

1. Firmilay (a Type III gold alloy).

The marginal widths of the cast Firmilay specimens were subjected to a two-factor analysis of variance (Table 11). The first factor in the analysis was the repeated measure of proximal and distal margin location for each specimen. The second factor in the analysis was the experimental sprue attachment design groups. Level 1 consisted of the Gradual Constricted sprue attachment design. Level 2 consisted of the Abrupt Constricted sprue attachment design. Level 3 consisted of the Flared sprue attachment design. Level 4 consisted of the Straight sprue attachment design. The dependent variable was the mean width of the cast meniscus (margin). The mean meniscus width and standard deviation for each is listed in Table 12 and demonstrated graphically in Figure 6. The raw data for the Firmilay test specimens are listed in Tables 25 and 26 in the Appendix.

The results of the ANOVA for Firmilay (Table 11) demonstrated the main effect of the repeated measure of widths of the proximal and distal margins for each group was significant ($p<.0001$). The main effect of the second factor (sprue attachment design) was also significant ($p<.0027$) across the groups. In addition, the interaction between the two factors was significant ($p<.0001$). In other words, the difference in meniscus width between the proximal and distal margins of the Firmilay specimens was inconsistent across the sprue attachment design groups.

For the proximal margin of the Firmilay specimens, the multiple pairwise analysis using the Scheffe F-test analysis of means revealed that the proximal margin (meniscus) width of the Straight sprue attachment group was significantly less than both the Gradual Constricted sprue attachment group ($p<.05$) and the Abrupt Constricted sprue attachment group ($p<.05$). The proximal margin (meniscus) width of the Flared sprue attachment group was also significantly less than both the Gradual Constricted sprue attachment group ($p<.05$) and the Abrupt Constricted sprue attachment group ($p<.05$).

The multiple pairwise analysis revealed no significant difference in cast proximal marginal width between the Straight and the Flared sprue attachment groups. However, the proximal margin width of the Gradual Constricted sprue attachment group was significantly less than the Abrupt Constricted sprue attachment group ($p<.05$). (Table 13)

TABLE 1. Correlation Matrix of the Four Independent Raters Using the Spearman Rank Correlation Coefficient (Rho)

	Rater 1	Rater 2	Rater 3	Rater 4
Rater 1	____	.856 *	.874 *	.794 *
Rater 2	.856 *	____	.829 *	.743 *
Rater 3	.874 *	.829 *	____	.758 *
Rater 4	.794 *	.743 *	.758 *	____

* Level of significance p<.001

TABLE 2. Kruskal-Wallis One Way Analysis of Mean Porosity Rank for Firmilay

Degrees of Freedom	3
Number of Groups	4
Number of Cases	40
H	12.514 *

* Level of significance $p<.01$

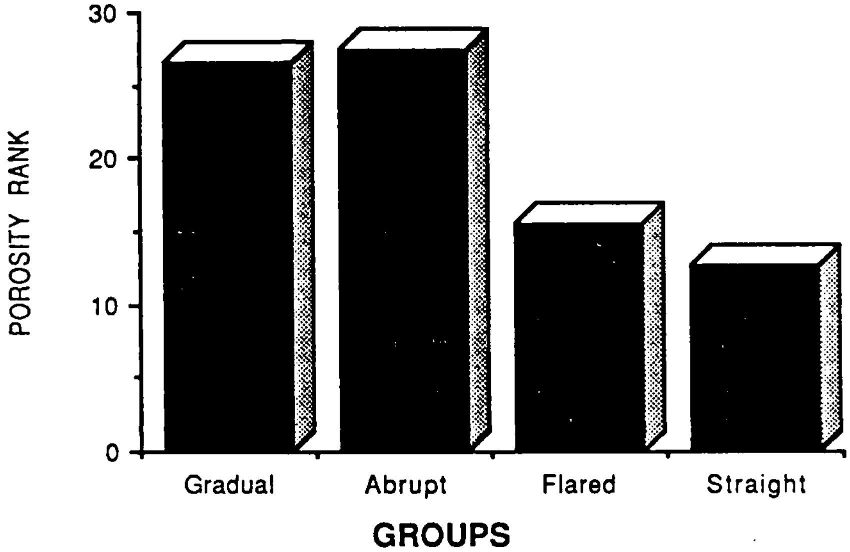
TABLE 3. Statistical Mean Rank of Porosity of the Sprue Attachment Groups for Firmilay

Sprue Attachment Design Group	Number of Cases	Mean Rank
Straight	10	12.6
Flared	10	15.5
Gradual Constricted	10	26.5
Abrupt Constricted	10	27.4

TABLE 4. Mann-Whitney Multiple Pairwise Comparison of Mean Porosity Rank for Firmilay

Group Comparison (mean rank)	U	Z	Level of significance
Straight (10.3) Flared (10.7)	48	-0.151	p=.44
Straight (6.75) Gradual (14.25)	12.5	-2.835	p<.01
Straight (6.55) Abrupt (14.45)	10.5	-2.986	p<.01
Flared (8.1) Gradual (12.9)	26	-1.814	p<.05
Flared (7.7) Abrupt (13.3)	22	-2.117	p<.05
Gradual (10.35) Abrupt (10.65)	48.5	-0.113	p=.45

FIGURE 3: Bar chart of the mean porosity rank of the sprue attachment design groups for Firmilay.



30
20
10
0
POROSITY RANK
Gradual
Abrupt
Flared
Straight
GROUPS

TABLE 5. Kruskal-Wallis One Way Analysis of Mean Porosity Rank for Jel-5

Degrees of Freedom	3
Number of Groups	4
Number of Cases	40
H	7.619 *

* Level of significance $p<.057$

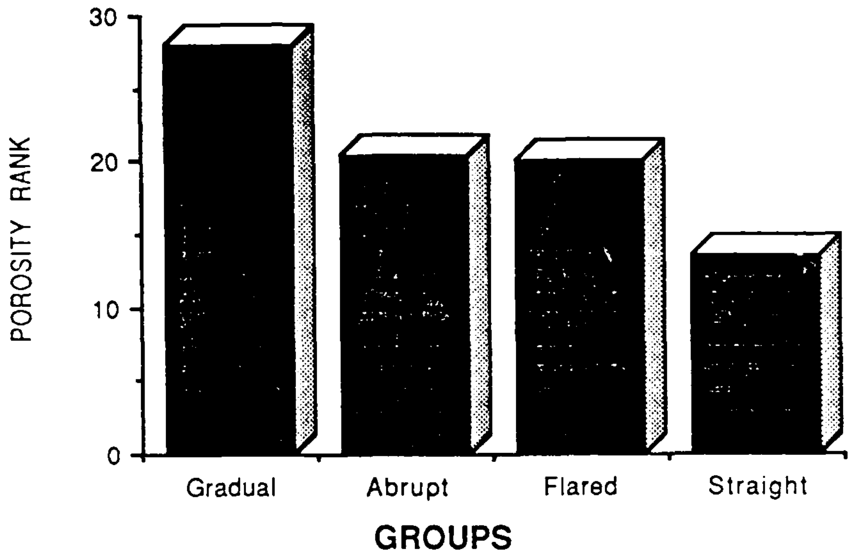
TABLE 6. Statistical Mean Rank of Porosity of the Sprue Attachment Groups for Jel-5

Sprue Attachment Design Group	Number of Cases	Mean Rank
Straight	10	13.6
Flared	10	20
Gradual Constricted	10	28
Abrupt Constricted	10	20.4

TABLE 7. Mann-Whitney Multiple Pairwise Comparison of Mean Porosity Rank for Jel-5

Group Comparison (mean rank)	U	Z	Level of significance
Straight (8.95) Flared (12.05)	34.5	-1.172	p=.120
Straight (7) Gradual (14)	15	-2.646	p<.010
Straight (8.65) Abrupt (12.35)	31.5	-1.398	p=.081
Flared (8.35) Gradual (12.65)	28.5	-1.625	p<.052
Flared (10.6) Abrupt (10.4)	49	-0.076	p=.223
Gradual (12.35) Abrupt (8.65)	31.5	-1.398	p=.081

FIGURE 4: Bar chart of the mean porosity rank of the sprue attachment design groups for Jel-5.



30
20
10
0
POROSITY RANK
Gradual
Abrupt
Flared
Straight
GROUPS

TABLE 8. Kruskal-Wallis One Way Analysis of Mean Porosity Rank for Rexillium III

Degrees of Freedom	3
Number of Groups	4
Number of Cases	40
H	5.108 *

* Not significant p=.17

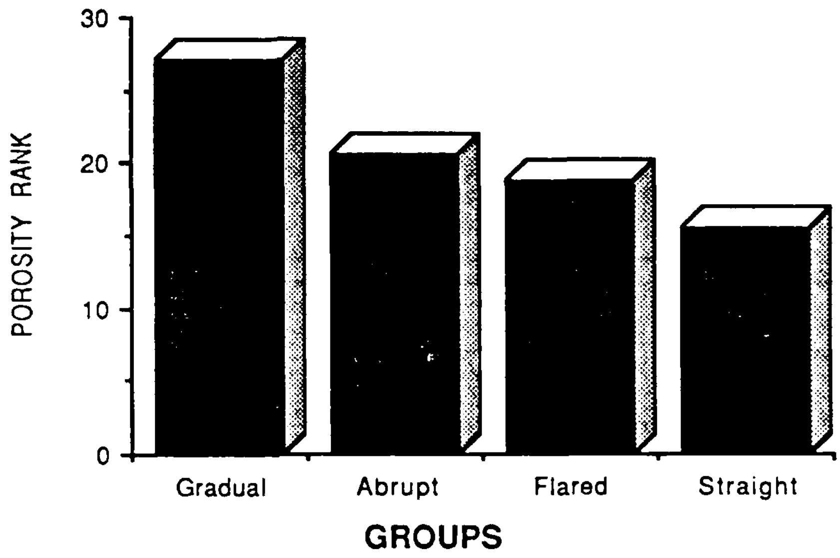
TABLE 9. Statistical Mean Rank of Porosity of the Sprue Attachment Groups for Rexillium III

Sprue Attachment Design Group	Number of Cases	Mean Rank
Straight	10	15.6
Flared	10	18.8
Gradual Constricted	10	27.05
Abrupt Constricted	10	20.55

TABLE 10. Mann-Whitney Multiple Pairwise Comparison of Mean Porosity Rank for Rexillium III

Group Comparison (mean rank)	U	Z	Level of significance
Straight (9.45) Flared (11.55)	39.5	-0.794	p=.213
Straight (7.9) Gradual (13.1)	24	-1.965	p<.05
Straight (9.25) Abrupt (11.75)	37.5	-0.945	p=.172
Flared (8.25) Gradual (12.75)	27.5	-1.701	p<.05
Flared (10) Abrupt (11)	45	-0.378	p=.352
Gradual (12.2) Abrupt (8.8)	33	-1.285	p=.099

FIGURE 5: Bar chart of the mean porosity rank of the sprue attachment design groups for Rexillium III.


30
20
10
0
POROSITY RANK
Gradual
Abrupt
Flared
Straight
GROUPS

The marginal widths of the cast Firmilay specimens were subjected to a two-factor analysis of variance (Table 11). The first factor in the analysis was the repeated measure of proximal and distal margin location for each specimen. The second factor in the analysis was the experimental sprue attachment design groups. Level 1 consisted of the Gradual Constricted sprue attachment design. Level 2 consisted of the Abrupt Constricted sprue attachment design. Level 3 consisted of the Flared sprue attachment design. Level 4 consisted of the Straight sprue attachment design. The dependent variable was the mean width of the cast meniscus (margin). The mean meniscus width and standard deviation for each is listed in Table 12 and demonstrated graphically in Figure 6. The raw data for the Firmilay test specimens are listed in Tables 25 and 26 in the Appendix.

The results of the ANOVA for Firmilay (Table 11) demonstrated the main effect of the repeated measure of widths of the proximal and distal margins for each group was significant ($p<.0001$). The main effect of the second factor (sprue attachment design) was also significant ($p<.0027$) across the groups. In addition, the interaction between the two factors was significant ($p<.0001$). In other words, the difference in meniscus width between the proximal and distal margins of the Firmilay specimens was inconsistent across the sprue attachment design groups.

For the proximal margin of the Firmilay specimens, the multiple pairwise analysis using the Scheffe F-test analysis of means revealed that the proximal margin (meniscus) width of the Straight sprue attachment group was significantly less than both the Gradual Constricted sprue attachment group ($p<.05$) and the Abrupt Constricted sprue attachment group ($p<.05$). The proximal margin (meniscus) width of the Flared sprue attachment group was also significantly less than both the Gradual Constricted sprue attachment group ($p<.05$) and the Abrupt Constricted sprue attachment group ($p<.05$).

The multiple pairwise analysis revealed no significant difference in cast proximal marginal width between the Straight and the Flared sprue attachment groups. However, the proximal margin width of the Gradual Constricted sprue attachment group was significantly less than the Abrupt Constricted sprue attachment group ($p<.05$). (Table 13)

For the distal margin of the Firmilay specimens, the multiple pairwise analysis using the Scheffe F-test analysis demonstrated that no significant difference existed between any of the following six sets of sprue attachment groups for the distal marginal width: Gradual Constricted & Abrupt Constricted, Gradual Constricted & Flared, Gradual Constricted & Straight, Abrupt Constricted & Flared, Abrupt Constricted & Straight, and Flared & Straight (Table 14).

From these results for Firmilay it can be inferred that the Straight and Flared sprue attachment groups had a significantly smaller cast proximal margin than either the Gradual Constricted or Abrupt Constricted sprue attachment groups. In addition, the Gradual Constricted sprue attachment group had a significantly smaller cast proximal margin width than the Abrupt Constricted sprue attachment group. The Straight sprue attachment design produced the smallest mean cast marginal width (140.022 microns), followed closely by the Flared sprue attachment design (144.744 microns). The Gradual Constricted sprue attachment design resulted in a mean cast marginal width of 150.278 microns and the Abrupt Constricted sprue attachment design produced a mean cast marginal width of 177.567 microns.

2. Jel-5 (a palladium-silver alloy).

The marginal widths of the cast Jel-5 specimens were subjected to a two-factor analysis of variance (Table 15). The first factor in the analysis was the repeated measure of the proximal and distal margin location for each specimen. The second factor in the analysis was the experimental sprue attachment design groups. Level 1 consisted of the Gradual Constricted sprue attachment design. Level 2 consisted of the Abrupt Constricted sprue attachment design. Level 3 consisted of the Flared sprue attachment design. Level 4 consisted of the Straight sprue attachment design. The dependent variable was the mean width of the cast meniscus (margin). The mean meniscus width and standard deviation for each is listed in Table 16 and represented graphically in Figure 7. The raw data for the Jel-5 test specimens are listed in Tables 27 and 28 in the Appendix.

The results of the ANOVA for Jel-5 (Table 15) demonstrated the main effect of the repeated measure of widths of the proximal and distal margins for each group was significant ($p<.0001$). The main effect of sprue attachment design was also significant ($p<.0047$) across the groups.

However, the interaction between the two factors was not significant (p=.9867). In other words, the difference in meniscus width between the proximal and distal margins was consistent across the sprue attachment design groups.

The multiple pairwise analysis utilizing the Scheffe F-test analysis of means revealed that no significant differences existed between any of the following six sets of sprue attachment groups in regards to cast marginal width for Jel-5: Gradual Constricted & Abrupt Constricted, Gradual Constricted & Flared, Gradual Constricted & Straight, Abrupt Constricted & Flared, Abrupt Constricted & Straight, and Flared & Straight (Table 17).

From these results for Jel-5 it can be inferred that no sprue attachment group demonstrated a significant superiority in regards to producing a smaller cast margin (meniscus). However, the Flared sprue attachment design produced the smallest mean cast marginal width (101.456 microns), followed closely by the Abrupt Constricted sprue design (106.122 microns). The Gradual Constricted sprue attachment resulted in a mean cast marginal width of 127.067 microns and the Straight sprue attachment produced a mean cast marginal width of 129.433 microns.

3. Rexillium III (a base-metal alloy).

The marginal widths of the cast Rexillium III specimens were subjected to a two-factor analysis of variance (Table 18). The first factor in the analysis was the repeated measure of proximal and distal margin location for each specimen. The second factor in the analysis was the experimental sprue attachment design groups. Level 1 consisted of the Gradual Constricted sprue attachment design. Level 2 consisted of the Abrupt Constricted sprue attachment design. Level 3 consisted of the Flared sprue attachment design. Level 4 consisted of the Straight sprue attachment design. The dependent variable was the mean width of the cast meniscus (margin). The mean meniscus width and standard deviation for each is listed in Table 19 and demonstrated graphically in Figure 8. The raw data for the Rexillium III test specimens are listed in Tables 29 and 30 in the Appendix.

The results of the ANOVA for Rexillium III (Table 18) demonstrated that the main effect of repeated measure of widths of the proximal and distal margins for each group was not significant (p=.0894). The main

effect of the second factor of sprue attachment design was significant ($p<.0093$). In addition, the interaction between the two factors was significant ($p<.0234$). In other words, the difference in meniscus width between the proximal and distal margins of the Rexillium III specimens was inconsistent across the sprue attachment design groups.

For the proximal margin of the Rexillium III specimens, the multiple pairwise analysis using the Scheffe F-test analysis of means revealed that the proximal margin (meniscus) width of the Flared sprue attachment group was significantly less than both the Abrupt Constricted sprue attachment group ($p<.05$) and the Straight sprue attachment group ($p<.05$). No significant difference in proximal margin width was demonstrated between the following sets of sprue attachment groups: Gradual Constricted & Abrupt Constricted, Gradual Constricted & Flared, Gradual Constricted & Straight, and Abrupt Constricted & Straight (Table 20).

For the distal margin of the Rexillium III specimens, the multiple pairwise analysis using the Scheffe F-test analysis demonstrated that no significant difference existed between any of the following six sets of sprue attachment groups for the distal marginal width: Gradual Constricted & Abrupt Constricted, Gradual Constricted & Flared, Gradual Constricted & Straight, Abrupt Constricted & Flared, Abrupt Constricted & Straight, and Flared & Straight (Table 21).

From these results for Rexillium III it can be inferred that the Flared sprue attachment group had a significantly smaller cast proximal margin than either the Abrupt Constricted or Straight sprue attachment groups. The Flared sprue attachment design resulted in the smallest mean cast marginal width (89.467 microns); however, this was not significantly smaller than the other three designs: Gradual Constricted (101.111 microns), Straight (103.422 microns), and Abrupt Constricted (106.578 microns).

TABLE 11. Two Factor Repeated Measures ANOVA for Firmilay

SOURCE	df	Sum of Squares	Mean Square	F-test	P value
GROUP (A) Repeated Measure Proximal & Distal Margin Widths	1	35032.223	35032.223	20.677	.0001
GROUP (B) Sprue Attachment Design	3	25422.455	8474.152	5.002	.0027
AB	3	46745.314	15581.771	9.197	.0001
Error	112	189756.652	1694.256		

TABLE 12. Table of Means for the Dependant Measure, Mean Meniscus Width (Microns), By Group and Location for Firmilay

Repeated Measure	Proximal	Distal	Totals
Straight	15 * 107.200 + 31.551 **	15 * 172.844 + 47.458 **	30 * 140.022 +
Flared	15 * 105.156 + 33.593 **	15 * 184.333 + 36.317 **	30 * 144.744 +
Gradual Constricted	15 * 146.267 + 40.604 **	15 * 154.289 + 44.715 **	30 * 150.278 +
Abrupt Constricted	15 * 185.644 + 40.017 **	15 * 169.489 + 51.083 **	30 * 177.567 +

* Number
\+ Mean
** Standard Deviation

TABLE 13. Multiple Pairwise Analysis of Mean Marginal Width of Proximal Margin for Firmilay

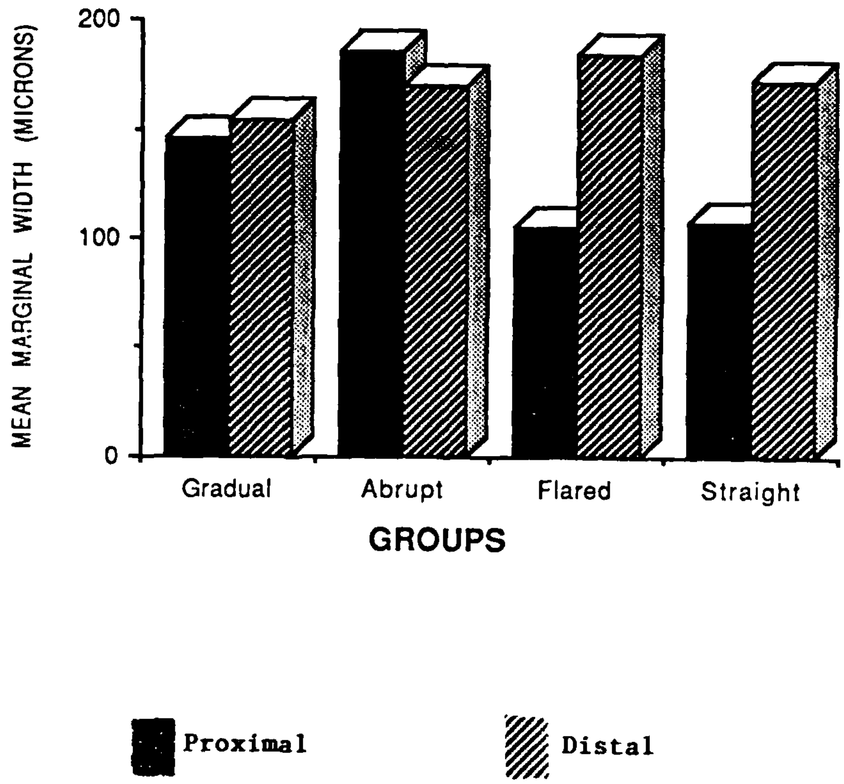
Comparison of Sprue Designs	Mean Difference	Scheffe F-test
Gradual vs Abrupt	-39.378	2.885 *
Gradual vs Flared	41.111	3.145 *
Gradual vs Straight	39.067	2.840 *
Abrupt vs Flared	80.489	12.055 *
Abrupt vs Straight	78.444	11.450 *
Flared vs Straight	-2.044	.008

* Level of significance $p<.05$

TABLE 14. Multiple Pairwise Analysis of Mean Marginal Width of Distal Margin for Firmilay

Comparison of Sprue Designs	Mean Difference	Scheffe F-test
Gradual vs Abrupt	-15.200	.282
Gradual vs Flared	-30.044	1.104
Gradual vs Straight	-18.556	.421
Abrupt vs Flared	-14.844	.269
Abrupt vs Straight	-3.356	.014
Flared vs Straight	11.489	.161

FIGURE 6: Bar chart of the mean marginal widths (microns) of the proximal and distal cast margins for the sprue attachment design groups for Firmilay.



MEAN MARGINAL WIDTH (MICRONS)
200
100
0
Gradual
Abrupt
Flared
Straight
GROUPS
Proximal
Distal

TABLE 15. Two Factor Repeated Measures ANOVA for Jel-5

Source	df	Sum of Squares	Mean Square	F-test	P value
GROUP (A) Repeated Measure Proximal & Distal Margin Widths	1	69296.112	69296.112	51.604	.0001
GROUP (B) Sprue Attachment Design	3	18361.062	6120.354	4.558	.0047
AB	3	186.284	62.095	.046	.9867
Error	112	150399.496	1342.853		

TABLE 16. Table of Means for the Dependant Measure, Mean Meniscus Width (Microns), By Group and Location for Jel-5

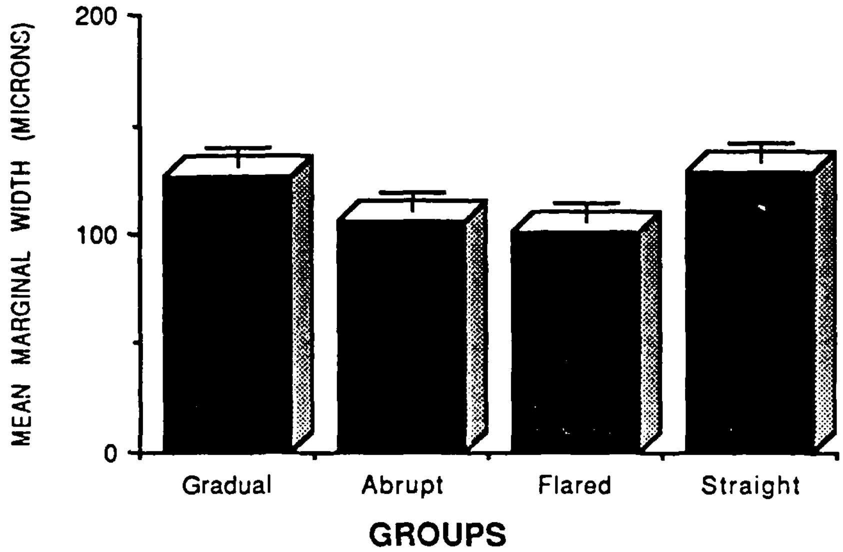
Repeated Measure	Proximal	Distal	Totals
Straight	15 * 105 +	15 * 153.867 +	30 * 129.433 + 40.26 **
Flared	15 * 75.578 +	15 * 127.333 +	30 * 101.456 + 43.851 **
Gradual Constricted	15 * 103.933 +	15 * 150.200 +	30 * 127.067 + 42.421 **
Abrupt Constricted	15 * 83.444 +	15 * 128.800 +	30 * 106.122 + 47.316 **

* Number
\+ Mean
** Standard Deviation

TABLE 17. Multiple Pairwise Analysis of Mean Marginal Widths for Jel-5

Comparison of Sprue Designs	Mean Difference	Scheffe F-test
Gradual vs Abrupt	20.944	1.157
Gradual vs Flared	25.611	1.730
Gradual vs Straight	-2.367	.015
Abrupt vs Flared	4.667	.057
Abrupt vs Straight	-23.311	1.433
Flared vs Straight	-27.978	2.065

FIGURE 7: Bar chart of the mean marginal widths (microns) of the cast margins for the sprue attachment design groups for Jel-5.



MEAN MARGINAL WIDTH (MICRONS)
200
100
0
Gradual
Abrupt
Flared
Straight
GROUPS

TABLE 18. Two Factor Repeated Measures ANOVA for Rexillium III

Source	df	Sum of Squares	Mean Square	F-test	P value
GROUP (A) Repeated Measure Proximal & Distal Margin Widths	1	1220.281	1220.281	2.936	.0894
GROUP (B) Sprue Attachment Design	3	5012.43	1670.81	4.02	.0093
AB	3	4100.044	1366.681	3.289	.0234
Error	112	46546.519	415.594		

TABLE 19. Table of Means for the Dependant Measure, Mean Meniscus Width (Microns), By Group and Location for Rexillium III

Repeated Measure	Proximal	Distal	Totals
Straight	15 * 108.667 + 25.941 **	15 * 98.178 + 20.695 **	30 * 103.422 +
Flared	15 * 83.711 + 18.830 **	15 * 95.222 + 11.331 **	30 * 89.467 +
Gradual Constricted	15 * 103.956 + 26.955 **	15 * 98.267 + 13.494 **	30 * 101.111 +
Abrupt Constricted	15 * 117.000 + 21.188 **	15 * 96.156 + 19.570 **	30 * 106.578 +

* Number
\+ Mean
** Standard Deviation

TABLE 20. Multiple Pairwise Analysis of Mean Marginal Width of Proximal Margin for Rexillium III

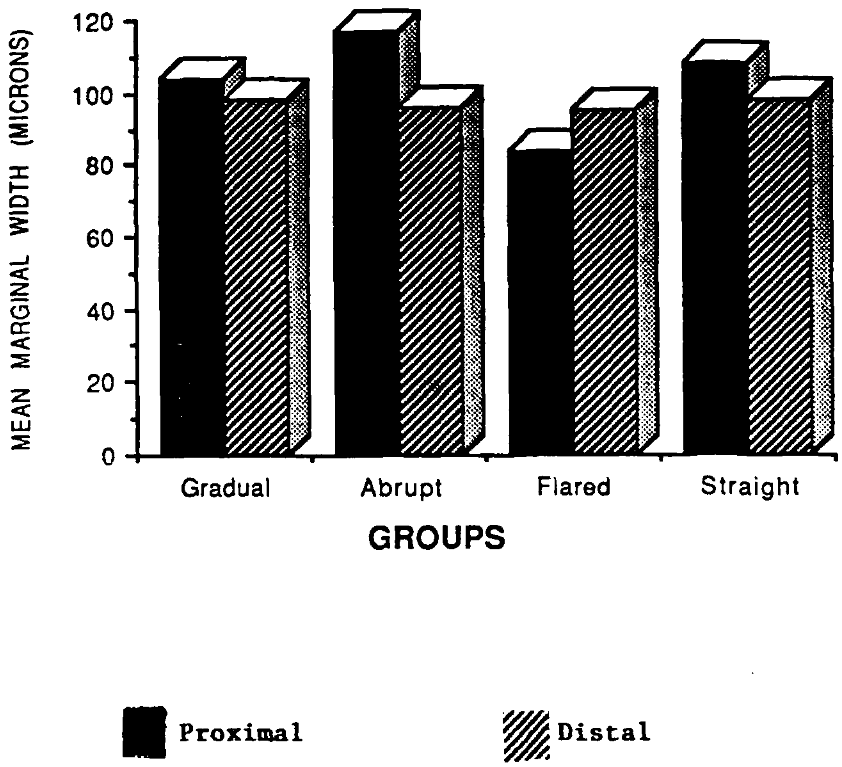
Comparison of Sprue Designs	Mean Difference	Scheffe F-test
Gradual vs Abrupt	-13.044	.772
Gradual vs Flared	20.244	1.860
Gradual vs Straight	-4.711	.101
Abrupt vs Flared	33.289	5.030 *
Abrupt vs Straight	8.333	.315
Flared vs Straight	-24.956	2.827 *

* Level of significance $p<.05$

TABLE 21. Multiple Pairwise Analysis of Mean Marginal Width of Distal Margin for Rexillium III

Comparison of Sprue Designs	Mean Difference	Scheffe F-test
Gradual vs Abrupt	2.111	.040
Gradual vs Flared	3.044	.083
Gradual vs Straight	.089	.007
Abrupt vs Flared	.933	.008
Abrupt vs Straight	-2.022	.036
Flared vs Straight	-2.956	.078

FIGURE 8: Bar chart of the mean marginal widths microns) of the proximal and distal cast margins for the sprue attachment design groups for Rexillium III.



MEAN MARGINAL WIDTH (MICRONS)
120
100
80
60
40
20
0
Gradual
Abrupt
Flared
Straight
GROUPS
Proximal
Distal

V. DISCUSSION

A critical consideration in obtaining successful cast dental restorations is the control of both porosity and castability. These important parameters have been evaluated with several different experimental designs. Those castability studies which have utilized wedge shaped patterns have demonstrated reproducible data sensitive to wax pattern orientation, burnout temperature, and casting temperature. A more convenient method for predicting castability has been shown using the mesh grid pattern. However, the path that the molten alloy must traverse in the mesh grid pattern is greatly different than the path seen when casting a complete veneer crown. The wedge pattern more closely approximates this pathway, but the direction of flow is not accurately reproduced.

Verrett and Duke (1989) developed a castability model which was capable of discriminating between experimental sprue attachment groups and satisfied many of the criteria for an ideal castability test. In addition to accurately reproducing the direction of molten alloy flow, his design utilizes two wedges, the axial walls of the pattern as seen in cross section, in the evaluation of castability.

Grundler (1980) has implied that the sprue attachment designs empirically observed to produce adequate castability can be uniformly applied to all alloys. No differentiation has been made for sprue attachment designs among the different classifications of dental casting alloys in many of the reference manuals and textbooks. The three alloys in this present study were selected based upon their specific gravity in order to evaluate the effect of various densities on sprue attachment geometry. Firmilay was the densest alloy of the three tested with a specific gravity of 15.5 gm/cc, followed by Jel-5 with a specific gravity of 10.7 gm/cc and Rexillium III with a specific gravity of 7.75 gm/cc.

Myers (1941) described an equation for centrifugal casting force: Casting Force = Proportionality Constant x Mass x Radius of Casting Arm x (Revolutions per Second)^2 or $F = KmrN^2$. As the density of the alloy decreases and the volume of the alloy remains constant, the casting force

this equation for casting force. Engleman and Blechner (1981) and Rousseau (1984) have recommended a Constricted sprue attachment design in order to increase the castability of non-noble alloys by increasing the velocity at which the molten alloy enters the mold space of the dental casting. Grundberg and Lutz (1985) have suggested the Venturi phenomenon as a possible mechanism for increasing the molten alloy's velocity and casting force, resulting in improved castability. McLean (1980) advocated the utilization of an Abrupt Constricted sprue design in order to obtain more complete castings.

The results of this present study agree with those of Nielsen and Ollerman (1976), Wagner (1980), Craig (1985), and Verrett and Duke (1989) in demonstrating superior castability of the Flared and Straight sprue attachment designs in casting Firmilay and the Flared sprue design in casting Rexillium III. Eventhough no significant differences were demonstrated with Jel-5, the data suggests that the Flared sprue attachment design resulted in the smallest mean cast meniscus width of the four designs tested. The finding in the present study that the Flared sprue attachment produced the smaller cast margin with Rexillium III, an alloy with low specific gravity, directly contradicts the results of McLean (1980), the recommendations of Engleman and Blechner (1981) and Rousseau (1984), and the suggestions of Grundberg and Lutz (1985).

A significant difference in regards to margin location was demonstrated for Firmilay and Rexillium III. In both cases the proximal margin revealed significant differences between sprue attachment groups. One would think that the distal margin would have demonstrated differences due to its location and relationship with casting force. However, the proximal margin being the more difficult to cast discriminated between the sprue attachment designs the best.

A comparison of mean cast meniscus widths revealed that Rexillium III cast the thinnest margin, followed by Jel-5 and then Firmilay. This finding that a base metal alloy (nickel-chromium-beryllium) produced better castability than a noble alloy is in agreement with the results reported by Hinman et al. (1985) and Covington et al. (1985). These two studies utilized a polyester mesh grid pattern while evaluating the castability of 18 and 32 alloys respectively. The results of this present

study support the observation by Hinman et al. that as mold and casting temperature increase so does castability.

The Straight and the Flared sprue attachment designs resulted in significantly less porosity in each of the three alloy tested. The same distribution of porosity was observed in the area of the sprue-crown junction as was reported by Verrett and Duke (1989). The occurrence of porosity was quite frequent in both the Abrupt and Gradual Constricted sprue attachment groups. This observation could have been the result of increased turbulence caused by the constricted sprue attachment designs. The results of this present study support the suggestion by Craig (1985), who recommended a flaring at the sprue attachment to allow for an even flow of molten alloy into the mold to minimize turbulence which in turn decreases porosity. By flaring the sprue, the fluidity of the molten alloy was maintained and the possibility of premature solidification was decreased, resulting in more complete castings.

Another reason for this observation of increased porosity with both Constricted sprue designs may have been the result of a localized heat build-up on the mold wall caused by the more localized stream of inrushing molten alloy with the constricted sprues and an increase in the velocity of the molten alloy as it entered the mold space. The results of Nielsen and Ollerman's study (1976) of suck-back porosity provides additional support for the previous interpretation. Nielsen and Ollerman stated that heat hysteresis during casting resulted in porosity in the area of the sprue-crown junction and could be avoided by flaring the sprue at its attachment to increase the area of the mold wall initially contacted by hot molten alloy. The results of this present investigation are in agreement with the observations of Nielsen and Ollerman (1976).

Further research utilizing this castability monitor could concentrate on use of different investments, additional alloys, and/or different combinations of the two. In addition, induction melting of alloys could be utilized and compared to torch melting. Accuracy of fit of the castings could also be investigated since such a study would be of significance from a clinical point of view.

VI. SUMMARY

The effects of four sprue attachment designs on the porosity and castability of three dental casting alloys were evaluated. The casting alloys included a Type III gold alloy (Firmilay), a palladium-silver alloy (Jel-5), and a base-metal alloy (Rexillium III). Porosity within the plane of section was investigated by rank ordering photographs of forty sectioned specimens for each alloy. Castability was evaluated by microscopic measurement of the widths of the sectioned and polished cast margin (meniscus).

The following conclusions were drawn:

1. For Firmilay, the Flared and Straight sprue attachment designs resulted in less porosity than the Gradual Constricted and Abrupt Constricted sprue attachment designs.

2. For Firmilay, no significant differences in porosity were demonstrated between the following sets of sprue attachment designs: Flared & Straight and Gradual Constricted & Abrupt Constricted.

3. For Jel-5, the Flared and Straight sprue attachment designs resulted in less porosity than the Gradual Constricted sprue attachment design.

4. For Jel-5, no significant differences in porosity were demonstrated between the following sets of sprue attachment designs: Flared & Straight, Flared & Abrupt Constricted, Straight & Abrupt Constricted, and Gradual Constricted & Abrupt Constricted.

5. For Rexillium III, the Flared and Straight sprue attachment designs resulted in less porosity than the Gradual Constricted sprue attachment design.

6. For Rexillium III, no significant differences in porosity were demonstrated between the following sets of sprue attachment designs: Flared & Straight, Flared & Abrupt Constricted, Straight & Abrupt Constricted, and Gradual Constricted & Abrupt Constricted.

7. For Firmilay, the Flared and Straight sprue attachment designs resulted in greater castability of the proximal margin than either the

Gradual Constricted sprue attachment design produced greater castability than the Abrupt Constricted sprue attachment design.

8. For Firmilay, no significant difference in castability was noted between the Flared and Straight sprue attachment designs in regards to the cast proximal margin. In addition, no significant differences were noted between the sprue attachment design groups in regards to the cast distal margin.

9. For Jel-5, no significant differences were noted between any of the sprue attachment design groups in regards to the cast marginal width. In other words, no sprue attachment design group demonstrated a significant superiority.

10. For Rexillium III, the Flared sprue attachment design resulted in greater castability of the proximal margin than either the Abrupt Constricted or Straight sprue attachment designs.

11. For Rexillium III, no significant differences were noted between the following pairs of sprue attachment designs for the cast proximal margin: Gradual Constricted & Abrupt Constricted, Gradual Constricted & Flared, Gradual Constricted & Straight, and Abrupt Constricted & Straight. In addition, no significant differences were noted between any of the sprue attachment design groups in regards to the cast distal margin.

12. A Flared or a Straight sprue attachment is recommended to minimize porosity with Firmilay, Jel-5, and Rexillium III.

13. A Flared or a Straight sprue attachment is recommended to optimize castability with Firmilay.

14. No definitive recommendation can be made concerning the castability of Jel-5.

15. A Flared sprue attachment is recommended to optimize castability of Rexillium III.

APPENDIX

TABLE 22. Rank Ordering of Percent Area Porosity On Photographs of the Sprue-Crown Junction by Four Independent Raters for Firmilay.

Photograph Number	Sprue Design	POROSITY RANK * #1	#2	#3	#4	Mean Rank
1	Gradual	26	33	33	38	32.50
2	Abrupt	32	39	39	17	31.75
3	Flared	7	6	9	15	9.25
4	Straight	13	23	13	7	14.00
5	Flared	8	4	8	9	7.25
6	Abrupt	9	7	11	16	10.75
7	Gradual	33	24	27	33	29.25
8	Straight	12	13	12	10	11.75
9	Abrupt	36	36	32	31	33.75
10	Flared	5	3	3	3	3.50
11	Gradual	15	20	26	25	21.50
12	Straight	3	5	1	1	2.50
13	Flared	38	28	29	26	30.25
14	Abrupt	24	27	21	23	23.75
15	Straight	23	26	25	27	25.25
16	Gradual	34	32	31	29	31.50
17	Gradual	40	35	38	30	35.75
18	Flared	10	10	7	12	9.75
19	Straight	17	17	19	19	18.00
20	Gradual	39	31	34	36	35.00
21	Abrupt	35	25	20	37	29.25
22	Straight	31	16	16	18	20.25
23	Flared	14	19	14	11	14.50
24	Gradual	30	29	17	21	24.25
25	Flared	1	2	2	2	1.75
26	Abrupt	22	12	23	22	19.75
27	Gradual	20	15	22	24	20.25
28	Straight	6	9	4	6	6.25
29	Flared	21	40	40	4	26.25
30	Abrupt	28	34	30	40	33.00
31	Straight	2	11	6	5	6.00
32	Gradual	27	22	18	34	25.25
33	Abrupt	19	21	24	39	25.75
34	Flared	18	14	10	20	15.50
35	Straight	11	8	15	13	11.75
36	Abrupt	29	30	28	32	29.75
37	Gradual	4	1	5	14	6.00
38	Flared	37	37	35	35	36.00
39	Straight	16	18	37	8	19.75
40	Abrupt	25	38	36	28	31.75

* Photographs ranked from least area of porosity (1) to greatest area of porosity (40).

TABLE 23. Rank Ordering of Percent Area Porosity On Photographs of the Sprue-Crown Junction by Four Independent Raters for Jel-5.

Photograph Number	Sprue Design	POROSITY RANK * #1	#2	#3	#4	Mean Rank
1	Gradual	33	26	34	34	31.75
2	Flared	16	16	11	11	13.50
3	Abrupt	19	12	5	2	9.50
4	Gradual	35	34	36	36	35.25
5	Straight	34	33	35	32	33.50
6	Abrupt	2	5	20	10	9.25
7	Straight	7	3	4	4	4.50
8	Abrupt	28	32	33	31	31.00
9	Flared	30	31	28	26	28.75
10	Gradual	36	36	37	37	36.50
11	Flared	15	18	12	9	13.50
12	Abrupt	39	38	40	40	39.25
13	Gradual	3	6	17	23	12.25
14	Straight	21	19	22	15	19.25
15	Flared	6	9	2	5	5.50
16	Abrupt	8	2	7	21	9.50
17	Straight	12	10	8	3	8.25
18	Abrupt	10	14	21	16	15.25
19	Abrupt	40	40	39	38	39.25
20	Gradual	27	23	30	28	27.00
21	Flared	11	17	10	12	12.50
22	Straight	1	8	1	1	2.75
23	Gradual	13	11	15	22	15.25
24	Straight	26	20	23	18	21.75
25	Abrupt	24	25	26	20	23.75
26	Straight	9	7	6	6	7.00
27	Flared	18	22	13	8	15.25
28	Gradual	38	39	38	39	38.50
30	Gradual	25	24	29	30	27.00
31	Flared	37	37	32	35	35.25
32	Straight	5	1	3	7	4.00
33	Abrupt	17	21	19	17	18.50
34	Gradual	20	28	31	27	26.50
35	Flared	32	30	27	33	30.50
36	Straight	23	13	25	19	20.00
37	Abrupt	4	4	16	14	9.50
38	Gradual	29	29	18	29	26.25
39	Flared	14	27	9	24	18.50
40	Straight	22	15	24	13	18.50

* Photographs ranked from least area of porosity (1) to greatest area of porosity (40).

TABLE 24. Rank Ordering of Percent Area Porosity On Photographs of the Sprue-Crown Junction by Four Independent Raters for Rexillium III.

Photograph Number	Sprue Design	POROSITY RANK * #1	#2	#3	#4	Mean Rank
1	Gradual	34	37	35	29	33.75
2	Straight	2	3	1	13	4.75
3	Abrupt	29	27	29	21	26.50
4	Flared	21	22	21	24	22.00
5	Straight	15	10	16	22	15.75
6	Gradual	35	17	34	20	26.50
7	Abrupt	7	6	7	1	5.25
8	Straight	8	13	9	15	11.25
9	Flared	14	21	13	16	16.00
10	Gradual	40	40	40	40	40.00
11	Straight	8	13	9	15	11.25
12	Abrupt	31	25	33	19	27.00
13	Flared	32	19	32	28	27.75
14	Straight	25	20	26	31	25.50
15	Abrupt	38	35	37	37	36.75
16	Gradual	9	7	8	14	9.50
17	Flared	37	23	38	27	31.25
18	Abrupt	10	11	10	9	10.00
19	Straight	16	14	15	6	12.75
20	Flared	11	9	11	4	8.75
21	Gradual	28	26	27	35	29.00
22	Abrupt	1	8	2	8	4.75
23	Flared	20	16	20	10	16.50
24	Straight	4	1	5	2	3.00
25	Gradual	39	29	39	39	36.50
26	Abrupt	30	30	30	23	28.25
27	Straight	6	4	6	11	6.75
28	Abrupt	13	28	14	25	20.00
29	Flared	12	15	12	17	14.00
30	Gradual	17	12	18	30	19.25
31	Abrupt	22	31	23	7	20.75
32	Gradual	24	32	22	33	27.75
33	Straight	23	33	24	36	29.00
34	Flared	26	34	25	18	25.75
35	Abrupt	27	24	28	26	26.25
36	Straight	19	18	17	12	16.50
37	Gradual	36	39	36	38	37.25
38	Flared	18	38	19	32	26.75
39	Gradual	5	5	4	5	4.75
40	Flared	3	2	3	3	2.75

* Photographs ranked from least area of porosity (1) to greatest area of porosity (40).

TABLE 25. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Firmilay. (Specimens 1 - 30)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
1	Gradual	232	228	228	229.3	168	167	168	167.7	198.5
2	Abrupt	143	148	146	145.7	157	151	154	154	149.9
3	Flared	155	152	152	153	157	160	163	160	156.5
4	Straight	160	157	158	158.3	158	158	155	157	157.7
5	Flared	107	102	106	105	197	198	199	198	151.5
6	Abrupt	242	244	243	243	194	191	192	192.3	217.7
7	Gradual	130	130	132	130.7	172	167	167	168.7	149.7
8	Straight	67	67	71	68.3	159	157	158	158	113.2
9	Abrupt	131	133	132	132	144	147	146	145.7	138.8
10	Flared	79	80	81	80	140	134	140	138	109
11	Gradual	124	125	127	125.3	176	174	174	174.7	150
12	Straight	88	86	85	86.3	198	196	199	197.7	142
13	Flared	55	57	56	55	118	117	116	117	86.5
14	Abrupt	127	128	132	129	179	177	178	178	153.5
15	Straight	122	121	122	121.7	222	216	218	218.7	170.2
16	Gradual	121	120	121	120.7	130	125	127	127.3	124
17	Gradual	173	168	169	170	174	174	173	173.7	171.8
18	Flared	124	123	124	123.7	176	172	178	175.3	149.5
19	Straight	86	83	88	85.7	138	140	136	138	111.8
20	Abrupt	210	210	210	210	177	181	175	177.7	193.8
21	Abrupt	160	159	158	159	128	131	129	129.3	144.2
22	Straight	110	107	106	107.7	190	193	190	191	149.3
23	Flared	145	146	150	147	238	239	240	239	193
24	Gradual	119	119	118	118.7	101	101	100	100.7	109.7
25	Flared	92	90	91	91	247	246	242	245.3	168
26	Abrupt	210	216	214	213.3	256	255	255	255.3	234.3
27	Gradual	180	184	182	182	102	100	100	100.7	141.3
28	Straight	71	69	70	70	194	195	193	194	132
29	Gradual	148	149	146	147.7	128	127	128	127.7	137.7
30	Abrupt	250	245	246	247	101	105	101	102.3	174.7

TABLE 26. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Firmilay. (Specimen Numbers 31 - 60)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
31	Straight	160	161	156	159	213	211	212	212	185.5
32	Flared	78	74	76	76	214	216	216	215.3	145.7
33	Gradual	123	126	127	125.3	90	96	88	91.3	108.3
34	Abrupt	161	155	157	157.7	179	186	185	183.3	170.5
35	Flared	97	98	99	98	211	207	210	209.3	153.7
36	Straight	74	72	70	72	283	279	280	280.7	176.4
37	Abrupt	159	156	158	157.7	157	158	157	157.3	157.5
38	Flared	108	107	110	108.3	173	170	174	172.3	140.3
39	Gradual	172	173	174	173	251	253	252	252	212.5
40	Straight	96	96	96	96	179	174	177	176.7	136.4
41	Gradual	213	211	214	212.7	204	206	205	205	208.9
42	Abrupt	174	173	177	174.7	130	129	130	129.7	152.2
43	Flared	174	177	174	175	167	171	165	167.7	171.4
44	Straight	93	94	93	93.3	131	128	134	131	112.2
45	Flared	116	114	117	115.7	162	162	165	163	139.4
46	Abrupt	232	235	230	232.3	227	230	228	228.3	230.3
47	Straight	82	83	86	83.7	88	87	89	88	85.9
48	Gradual	136	142	143	140.3	116	115	118	116.3	128.3
49	Gradual	110	113	112	111.7	196	196	198	196.7	154.2
50	Flared	60	60	63	61	221	222	224	222.3	141.7
51	Straight	144	145	144	144.3	134	132	130	132	138.2
52	Abrupt	214	214	214	214	273	270	272	271.7	242.9
53	Abrupt	204	207	208	206.3	134	135	138	135.7	171
54	Straight	136	133	135	134.7	188	195	193	192	163.4
55	Flared	88	91	86	88.3	168	171	168	169	128.7
56	Gradual	72	74	75	73.7	168	169	168	168.3	121
57	Flared	98	102	98	99.3	175	174	172	173.7	136.5
58	Abrupt	164	162	163	163	101	102	102	101.7	132.4
59	Gradual	134	133	132	133	144	142	145	143.7	138.4
60	Straight	127	125	129	127	125	125	128	126	126.5

TABLE 27. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Jel-5. (Specimen Numbers 1 - 30)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
1	Gradual	74	72	74	73.3	86	85	84	85	79.2
2	Abrupt	48	47	48	47.7	161	159	156	158.7	103.2
3	Flared	153	153	156	154	163	160	159	160.7	158.4
4	Straight	136	136	135	135.7	152	155	156	154.3	145
5	Flared	90	89	86	88.3	175	178	176	176.3	132.3
6	Abrupt	59	60	59	59.3	148	145	146	146.3	102.8
7	Gradual	128	132	132	130.7	162	168	163	164.3	147.5
8	Straight	50	48	49	49	181	180	180	180.3	114.7
9	Abrupt	43	43	41	42.3	83	82	83	82.7	62.5
10	Flared	35	32	34	33.7	115	114	115	114.7	74.2
11	Gradual	113	109	110	110.7	211	208	212	210.3	160.5
12	Straight	118	117	118	117.7	165	163	165	164.3	141
13	Flared	81	84	85	83.3	127	131	130	129.3	106.3
14	Abrupt	117	120	119	118.7	121	122	122	121.7	120.2
15	Straight	150	149	149	149.3	186	187	184	185.7	167.5
16	Gradual	75	71	73	73	88	83	87	86	79.5
17	Gradual	74	79	78	77	150	148	147	148.3	112.7
18	Flared	50	51	50	50.3	129	127	125	127	88.7
19	Straight	131	129	134	131.3	177	178	177	177.3	154.3
20	Abrupt	51	52	52	51.7	138	139	138	138.3	95
21	Abrupt	138	143	138	139.7	89	86	84	86.3	113
22	Straight	117	116	117	116.7	170	171	172	171	143.9
23	Flared	74	77	74	75	150	151	150	150.3	112.7
24	Gradual	115	112	115	114	161	161	162	161.3	137.7
25	Flared	72	73	73	72.7	115	117	119	117	94.9
26	Abrupt	93	93	95	93.7	76	75	79	76.7	85.2
27	Gradual	81	83	82	82	123	125	124	124	103
28	Straight	71	70	74	71.7	191	189	188	189.3	130.5
29	Gradual	132	132	130	131.3	133	131	132	132	131.7
30	Abrupt	75	75	74	74.7	210	212	211	211	142.9

TABLE 28. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Jel-5. (Specimen Numbers 31 - 60)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
31	Straight	35	38	35	36	142	140	142	141.3	88.7
32	Flared	40	39	39	39.3	160	161	160	160.3	99.8
33	Gradual	119	116	117	117.3	157	156	158	157	137.2
34	Abrupt	51	51	50	50.7	97	98	99	98	74.3
35	Flared	107	107	109	107.7	106	108	110	108	107.8
36	Straight	119	120	121	120	125	126	124	125	122.5
37	Abrupt	110	112	113	111.7	81	82	83	82	96.8
38	Flared	42	40	41	41	78	76	77	77	59
39	Gradual	172	169	171	170.7	112	115	118	115	142.8
40	Straight	122	120	122	121.3	161	161	163	161.7	141.5
41	Gradual	115	117	118	116.7	116	114	113	114.3	115.5
42	Abrupt	51	48	49	49.3	136	137	132	135	92.2
43	Flared	33	34	35	34	122	121	124	122.3	78.2
44	Straight	102	103	107	104	117	120	117	118	111
45	Flared	137	140	140	139	116	116	117	116.3	127.7
46	Abrupt	105	105	104	104.7	178	176	177	177	140.8
47	Straight	54	52	55	53.7	86	87	84	85.7	69.7
48	Gradual	128	132	132	130.7	180	186	180	182	156.3
49	Gradual	58	55	60	57.7	164	172	169	168.3	113
50	Flared	44	44	44	44	149	148	148	148.3	96.2
51	Straight	117	116	115	116	154	156	158	156	136
52	Abrupt	180	181	182	181	131	134	133	132.7	156.8
53	Abrupt	55	57	58	56.7	89	90	88	89	72.8
54	Straight	142	145	142	143	168	163	164	165	154
55	Flared	36	39	40	38.3	70	73	74	72.3	55.3
56	Gradual	90	85	85	86.7	190	184	187	187	136.8
57	Flared	134	131	134	133	128	130	132	130	131.5
58	Abrupt	70	70	70	70	196	197	197	196.7	133.3
59	Gradual	88	84	90	87.3	219	218	217	218	152.7
60	Straight	109	109	111	109.7	132	134	133	133	121.3

TABLE 29. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Rexillium III. (Specimen Numbers 1 - 30)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
1	Gradual	94	94	94	94	81	78	78	79	86.5
2	Abrupt	97	95	99	97	79	82	84	81.7	89.4
3	Flared	67	68	66	67	102	97	96	98.3	82.7
4	Straight	169	168	173	170	72	73	79	74.7	122.4
5	Flared	91	95	92	92.7	100	102	99	100.3	96.5
6	Abrupt	115	118	116	116.3	81	82	79	80.7	98.5
7	Gradual	101	101	102	101.3	103	104	107	104.7	103
8	Straight	103	103	99	101.7	122	126	121	123	112.4
9	Abrupt	175	180	177	177.3	94	98	93	95	136.2
10	Flared	85	87	84	85.3	100	104	101	101.7	93.5
11	Gradual	108	107	106	107	108	112	110	110	108.5
12	Straight	116	113	114	114.3	116	117	118	117	115.7
13	Flared	111	110	111	110.7	82	84	86	84	97.4
14	Abrupt	91	94	94	93	73	73	75	73.7	83.4
15	Straight	110	112	111	111	78	84	82	81.3	96.2
16	Gradual	75	74	73	74	114	114	112	113.3	93.7
17	Gradual	111	113	110	111.3	80	80	78	79.3	95.3
18	Flared	53	51	52	52	94	95	94	94.3	73.2
19	Straight	95	97	95	95.7	53	58	56	55.7	75.7
20	Abrupt	105	107	106	106	73	73	70	72	89
21	Abrupt	94	96	95	95	84	83	82	83	89
22	Straight	113	115	115	114.3	109	106	109	108	111.2
23	Flared	85	87	86	86	103	104	103	103.3	94.7
24	Gradual	100	100	101	100.3	101	103	102	102	101.2
25	Flared	100	102	100	100.7	114	112	113	113	106.9
26	Abrupt	127	128	127	127.3	134	131	131	132	129.7
27	Gradual	112	114	115	113.7	111	109	111	110.3	112
28	Straight	94	95	93	94	95	94	96	95	94.5
29	Gradual	56	55	54	55	99	99	99	99	77
30	Abrupt	121	120	122	121	124	120	120	121.3	121.2

TABLE 30. Mean Width (Microns) of the Proximal and Distal Margins, Derived from Three Measurements, and Mean Specimen Width for Rexillium III. (Specimen Numbers 31 - 60)

SPECIMEN		PROXIMAL				DISTAL				SPECIMEN
#	Design	#1	#2	#3	Mean	#1	#2	#3	Mean	MEAN
31	Straight	80	83	82	81.7	114	113	113	113.3	97.5
32	Flared	102	103	103	102.7	97	94	95	95.3	99
33	Gradual	159	159	157	158.3	116	117	114	115.7	137
34	Abrupt	105	105	103	104.3	87	86	88	87	95.7
35	Flared	100	98	102	100	83	86	84	84.3	92.2
36	Straight	123	126	124	124.3	90	90	88	89.3	106.8
37	Abrupt	134	132	131	132.3	112	112	112	112	122.2
38	Flared	68	71	70	69.7	104	106	108	106	87.9
39	Gradual	117	117	120	118	97	98	98	97.7	107.9
40	Straight	113	112	110	111.7	91	89	93	91	101.4
41	Gradual	118	118	117	117.7	113	114	113	113.3	115.5
42	Abrupt	126	124	124	124.7	109	108	109	108.7	116.7
43	Flared	79	81	79	79.7	79	78	78	78.3	79
44	Straight	119	121	118	119.3	99	97	99	98.3	108.8
45	Flared	92	91	93	92	98	97	97	97.3	94.7
46	Abrupt	123	123	123	123	92	93	91	92	107.5
47	Straight	75	78	79	77.3	101	99	102	100.7	89
48	Gradual	115	115	115	115	94	93	94	93.7	104.4
49	Gradual	93	93	93	93	79	78	76	77.7	85.4
50	Flared	53	55	53	53.7	72	75	73	73.3	63.5
51	Straight	76	76	78	76.7	83	85	84	84	80.4
52	Abrupt	100	103	102	101.7	89	88	91	89.3	95.5
53	Abrupt	108	108	107	107.7	84	85	87	85.3	96.5
54	Straight	88	90	88	88.7	102	101	103	102	93.4
55	Flared	63	61	63	62.3	91	89	90	90	76.2
56	Gradual	138	140	139	139	81	81	83	81.7	110.4
57	Flared	101	101	102	101.3	109	109	108	108.7	105
58	Abrupt	128	127	130	128.3	130	129	127	128.7	128.5
59	Gradual	63	62	60	61.7	97	96	97	96.7	79.2
60	Straight	148	151	149	149.3	138	141	139	139.3	144.3

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VITA

John Alan Levon [redacted] son of John J. and Corinne J. Levon. He graduated from Highland High School in Anderson, Indiana in 1971 and entered Indiana University during the fall of that same year. In November of 1974 he was elected into Phi Beta Kappa and in January of 1975 he was awarded a Bachelor of Arts degree, with distinction, in Biological Sciences.

He entered Indiana University School of Dentistry in August of 1974 and received a Doctor of Dental Surgery degree on May 10, 1978. In June of 1978 he accepted a commission in the United States Air Force and entered a General Practice Residency Program at Barksdale Air Force Base, Louisiana. He married Kathy L. Bickwermert on July 14, 1979.

From July of 1979 through July of 1984 he was assigned to Hill Air Force Base, Utah, where he served as the Chief of Prosthodontic Services. In August of 1984 he was reassigned to Wurtsmith Air Force Base, Michigan, where he again served as Chief of Prosthodontic Services until his reassignment in June of 1986. During this time in Michigan, his son, Matthew John, was born on October 3, 1985.

In July of 1986 he entered the Post-Doctoral Prosthodontic Program at the University of Texas Health Science Center at San Antonio. In August of 1987 he was admitted as a candidate for the Master of Science degree at the Graduate School of Biomedical Sciences. This Thesis is submitted for partial fulfillment of a Master of Science degree to be awarded upon completion of requirements, December 1990, from the University of Texas Health Science Center at San Antonio.

He completed a one-year fellowship in Maxillofacial Prosthetics at Wilford Hall Medical Center, Lackland Air Force Base, Texas on June 30, 1990. He has been assigned the position of Staff Prosthodontist at Yokota Air Base, Japan. He will assume this position in October, 1990.